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CONTENTS

Mechanism of Detonation in Explosives — *Robert W. Lawrence* — 1

Frequency Discrimination in the Low Velocity Zone — *T. R. Shugart* — 19

The Equation of Motion of a Geophone on the Surface of an Elastic Earth — *Alfred Wolf* — 29

Sand and Gravel Prospecting by the Earth Resistivity Method — *Stanley W. Wilcox* — 36

Magnetic Interpretation — *Dart Wantland* — 47

Association of Magnetic and Density Contrasts with Igneous Rock Classifications — *L. L. Nettleton and T. A. Elkins* — 60

Correlation of Gravity Observations with the Geology of the Smoothingiron Granite Mass, Llano County, Texas — *Frederick Romberg and Virgil E. Barnes* — 79

The Periodic Variations of the Gravitational Force. I. *Arthur E. Lockenvitz* — 94

Patents — 106

Publications Received — 115

Contributors — 117

The Society Round Table — 120

- Announcements of 1944 Annual Meeting — 120
- Official Ballot — 121
- Nominees for 1944-45 Executive Committee — 122
- Membership Applications Approved for Publication — 125

Personal Items — 127

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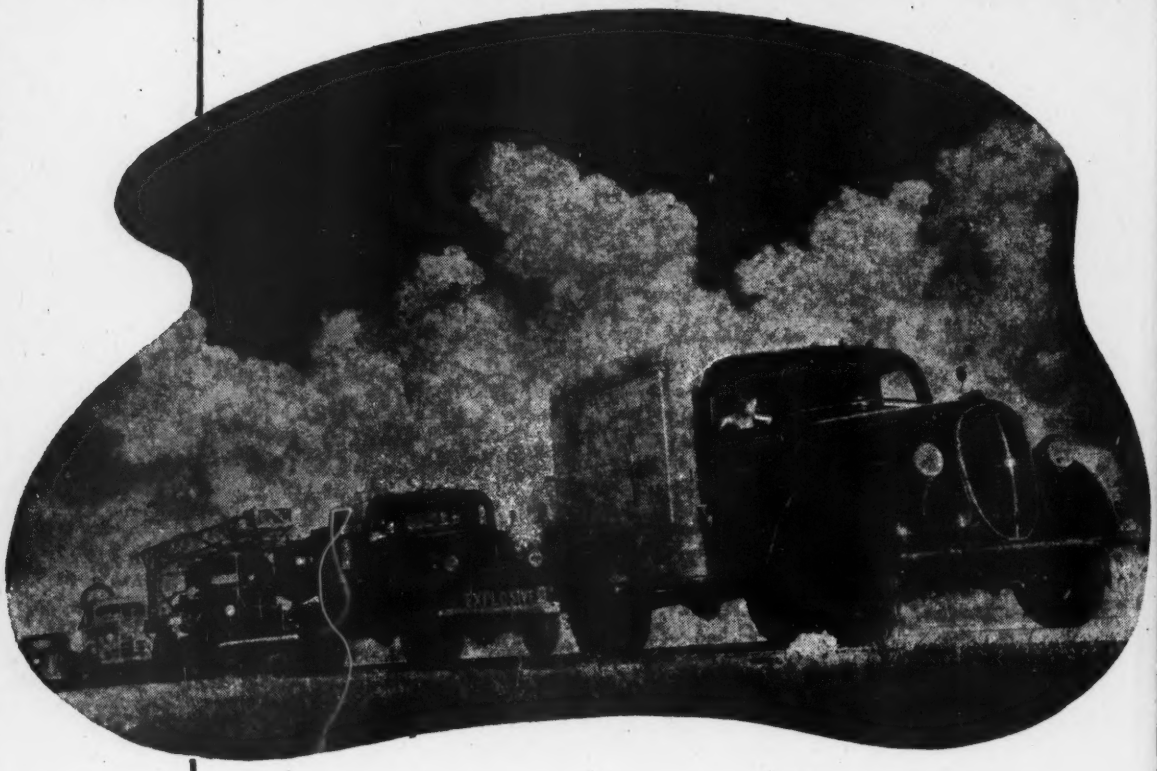

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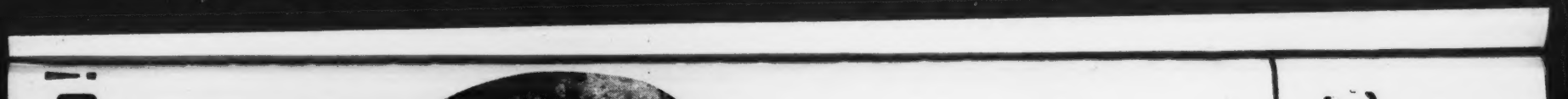

VOLUME IX JANUARY, 1944 NUMBER 1

GEOPHYSICS

A Journal of General and Applied Geophysics

MECHANISM OF DETONATION IN EXPLOSIVES*

ROBERT W. LAWRENCE†

ABSTRACT

Results of photographic work on the detonation of high explosives are presented and discussed in their relationship to the hydrodynamic theory of detonation. The two most important properties of an explosive are its strength and its detonation velocity. Methods for determining these quantities are described.

A moving film camera of the rotating drum type is especially useful in determining detonation velocity and in studying the nature of detonation. The photographic results, which are illustrated by a number of pictures, are helpful in demonstrating various elements of the theory. These photographs illustrate the nature of detonation waves in explosives and of shock waves in air. The duration of the detonation waves in nitroglycerin and blasting gelatin is less than one millionth of a second and the duration of the shock waves produced by these explosives in air is of the same order. The high temperature of shock waves which is predicted by theory is confirmed by the intense luminosity shown in photographs. The relatively low temperature predicted for shock waves in liquids is similarly confirmed by the absence of luminous shock waves in water.

Photographs are included showing the propagation of detonation from one cartridge of blasting gelatin to another across air gaps and water gaps. In the latter case no visible shock wave is produced in the water and the highly luminous after-burning is eliminated.

Calculated values of the detonation velocity for nitroglycerin, blasting gelatin and 60% gelatin dynamite are in approximate agreement with the experimentally determined values. Calculations indicate that pressures in the detonation wave may run as high as 140,000 atmospheres and temperatures to 4300°C.

The shape of the detonation wave front in a high velocity explosive like blasting gelatin is apparently planar whereas in low velocity explosives it is convex.

The actual mechanism of energy propagation in detonation is not clearly understood but probably involves activation of the explosive at the detonation wave front by high velocity products of the detonation which are projected forward at speeds even greater than the detonation velocity.

INTRODUCTION

In the seismic method of prospecting for oil, the blast of an explosive charge is used as the source of energy for the sound waves

* Presented at the annual meeting, Fort Worth, Texas, April 1943.

† Hercules Experiment Station, Hercules Powder Company, Wilmington, Delaware.

which are needed to explore underground strata. With this in mind, it is hoped that a study of explosive decomposition in which elements of theory and results of photographic investigations are combined will give a picture of explosive detonation which may prove helpful to geophysicists.

Explosive decomposition is of two types: burning and detonation. Black powder and smokeless powder burn while other explosives, like the commercial dynamites and the bursting charges for bombs, detonate. The two types of decomposition may differ in mechanism, but the most obvious difference is in the velocity with which they take place. Thus, in the case of smokeless powder, the combustion progresses into the powder grains at a linear velocity which amounts at most to a few centimeters per second and which is proportional to the pressure. Detonation of high explosives, however, involves an extremely rapid decomposition of the explosive molecules. This takes place in a reaction zone or detonation wave which travels through the explosive at a velocity, depending on the explosive and its density, between the limits of 1500 and 8500 m./sec. The velocity of the detonation wave is essentially independent of external pressure.

It is important to observe that the difference in the effects produced by burning and detonating explosives lies not in the quantity of energy produced, but in rate at which it is released. In fact, the same explosive can often either burn or detonate. Thus dynamite, when primed with a blasting cap, detonates with an ear-splitting noise and a shattering effect on the surroundings, but, when spread on the ground and ignited with a flame, burns vigorously but quietly. Some explosives, the primary or initiating type, readily go from combustion to detonation. For example, diazodinitrophenol, mercury fulminate, and lead azide, which belong to this class, may be caused to detonate by application of a very small amount of heat and thus may be used to initiate detonation in the less sensitive dynamites. In this way they form the basis of commercial blasting and electric blasting caps.

The existence of the detonation wave was discovered over sixty years ago by Berthelot[1] in studies on gaseous explosions.* The concept of the detonation wave in a column of explosive is illustrated by the schematic diagram in Fig. 1, taken from an article by Langweiler.[2] On the right of the diagram is the undecomposed explosive, in the middle and moving to the right at a velocity D is the detonation wave, and following the detonation wave are the hot gases traveling at the "flow

* All literature references are to be found at the end of the paper.

velocity" W. In the detonation wave the explosive molecules are transformed from solids or liquids at room temperature and normal pressure to gases at a temperature of perhaps 4000°C and a pressure of the order of 100,000 atmospheres. All of this happens in something less than a millionth of a second; and the length of the detonation zone may be measured in millimeters.

PROPERTIES OF EXPLOSIVES

The two properties of an explosive which are of outstanding importance are its strength and its detonation velocity. The strength, which

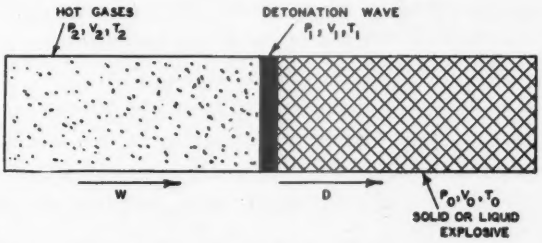

FIG. 1. DETONATION OF AN EXPLOSIVE COLUMN. The detonation wave or zone is moving to the right in a column of explosive at the detonation velocity, D. The solid or liquid explosive to the right of the detonation wave is still in its initial state, while to the left the gaseous products of the explosive are traveling along behind the detonation wave at the flow velocity, W. In the detonation zone the solid or liquid is transformed to gas in less than a millionth of a second at a density even greater than that of the original explosive and at a pressure of possibly 100,000 atmospheres. The gases behind the detonation wave are at a somewhat lower temperature and pressure. These gases will usually disrupt the strongest confinement and expand outwards.

is a measure of the work it can do, may be measured by ballistic methods or calculated thermodynamically. The detonation velocity can be measured by various means, and recently the hydrodynamic theory of detonation has been sufficiently developed so that the detonation velocity can be calculated with a fair degree of accuracy from quantities expressed in terms of temperature, pressure, and volume or density.

EXPLOSIVE STRENGTH

Methods used for measuring the strength of explosives include the ballistic mortar, the ballistic pendulum, and the Trauzl block. The ballistic mortar[3] consists of a heavy steel cylinder suspended as a pendulum. An explosive charge in the cylinder is confined by means of

a steel slug. When the explosive charge is fired the slug is blown out and the recoil of the pendulum is measured. The height of the swing gives a measure of the strength of the explosive. This is normally obtained in comparison with the strength of a standard explosive such as blasting gelatin or 40% straight dynamite. The ballistic mortar is used by explosives manufacturers for standardizing the strengths of dynamites.

The ballistic pendulum is similar in principle to the ballistic mortar although the operation differs somewhat. In this case a charge of dynamite is placed in a cannon and stemmed with a weighed charge of clay. This stemming is blown by the explosion into a mortar-shaped pendulum whose swing or deflection is measured. The charge of explosive required to give the same deflection as a standard charge of dynamite is determined. This method is used at the Bureau of Mines[4] in tests on permissible dynamites particularly.

The Trauzl block test has been much used abroad, especially in Germany, for measuring explosive strengths. In this test an explosive charge is fired, suitably tamped in a small cavity in a lead block, and the expansion of the cavity is used as a measure of the explosive strength.[5]

The strength of an explosive can also be calculated thermodynamically from the energy produced in its explosion. It is necessary to calculate the composition of the gases produced and the energy of decomposition. From the quantity of gas produced and the average specific heat, the temperature of explosion is computed. The temperature rise produced by the explosion is equal to the heat of the explosion Q, divided by the mean heat capacity of the gas, C_v. The temperature of the explosion is then given in degrees Kelvin by Eq. 1,

$$T = \Delta t + t_1 + 273 = Q/C_v + t_1 + 273. \qquad (1)$$

The so-called "hot-volume" of the gases has been found to give a good measure of the relative strength of explosives. This is given by

$$f = PV = n\,RT, \qquad (2)$$

in which

P = pressure of explosion gases
V = volume of explosion gases
n = number of moles of gas
R = gas constant
T = explosion temperature in degrees absolute

Methods of calculating the explosive strength have been described by

Berthelot, Kast, Jouguet, and others including Nash and Martin[6] and F. W. Brown.[7]

MEASUREMENT OF DETONATION VELOCITY

A number of methods devised for measuring velocity of detonation in explosives have been described in a review by Selle.[8] Of these, those most commonly used are the spark chronograph method of Mettegang[9] and the comparative Dautriche method.[10] A moving-film camera is

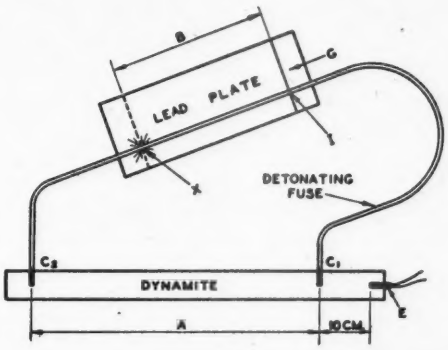

FIG. 2. DAUTRICHE METHOD OF MEASURING DETONATION VELOCITY. Detonation starts at blasting cap, E, and progresses through dynamite which initiates detonation in fuse at C_1 and C_2. Detonation waves in two branches of fuse meet at X making a mark on the plate. The midpoint, I, of the fuse is set against the line, G, on the lead plate, and the distance GX is measured. Then the detonation velocity of the dynamite is given by $V = AR/2B$, where R is the detonation velocity of the fuse.

also useful for this purpose and provides much other interesting information about the detonation.

In the spark chronograph method, a smoked drum is run at a known speed, and sparks generated by the breaking of electrical circuits passing through a column of explosive at a measured distance apart jump from discharge points to the drum. From the distance between the two marks on the drum, the known speed of the drum, and the distance between the wires, it is possible to calculate the detonation velocity.

The Dautriche method is a very useful one for determining detonation velocity with a minimum amount of equipment. In this method a detonating fuse such as Cordeau or Primacord is standard-

ized by an absolute method such as that of Mettegang, and its velocity is compared with that of the unknown explosive. This procedure is sufficiently illustrated in Fig. 2 to require no additional discussion.

Perhaps the most accurate method for measuring the detonation velocity is with a moving-film camera. Such cameras have been described by a number of investigators, including Lafitte,[11] Jones,[12] Payman, Shepherd, and Woodhead,[13] and R. W. Cairns.[14]

The rotating-drum camera constructed by Dr. R. W. Cairns,

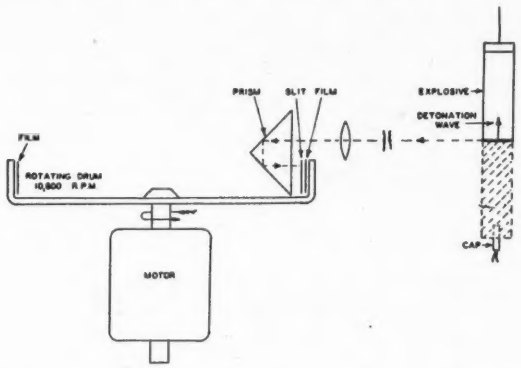

FIG. 3. ROTATING-DRUM CAMERA. Inner circumference of drum is 1 meter, giving a film speed of 180 m./sec. A slit 0.10 mm. wide adjacent to the film restricts field of view to a narrow band. Resolving time is about 0.5×10^{-6} sec.

Director of the Hercules Experiment Station, is shown in diagram in Fig. 3. When a cartridge of explosive is hung vertically so that the detonation travels at right angles to the direction of motion of the film as illustrated here, a photograph of the detonation is obtained which produces a sloping trace on the film. The detonation velocity is shown by the relationship:

$$D = \text{film speed} \times \text{slope} \times \frac{\text{Object size}}{\text{Image size}}$$

The steeper the line on the film, the greater is the detonation velocity.

PHOTOGRAPHS OF DETONATION: THEORY

The detonation of nitroglycerin in a glass tube is shown in Fig. 4. The bottom half represents the detonation of nitroglycerin, the line of intense luminosity being produced by the detonation wave which travels upward through the explosive. When the detonation wave

reaches the end of the nitroglycerin column, a shock wave or compression wave is produced in the air which is even more luminous than the detonation wave. Its initial velocity is even higher than that of the nitroglycerin, but decreases gradually and eventually assumes the

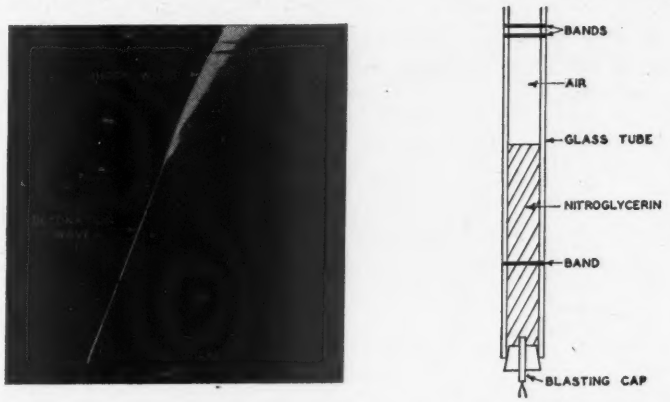

FIG. 4. DETONATION OF NITROGLYCERIN. The nitroglycerin container was a 10-mm. i.d. glass tube. The detonation wave travels the length of the nitroglycerin column vertically upward while film is traveling to the left, thus giving rise to a sloping trace on the film. When the detonation has reached the end of the column, a shock wave is produced in the air which is even more luminous than the detonation wave; this indicates a higher temperature. Intensity of radiation from the detonation wave is approximately 1,000,000 times that from a fluorescent lamp. The black bands are caused by pieces of black tape wrapped around the tube. These cut off the light until they are broken by the expanding gases. The dark zone immediately to the right of the detonation wave persists for about 5 millionths of a second and apparently represents the time required for the glass tube to disintegrate. After this the gases mixing with the air undergo further reactions and again become luminous. The slope of these streamers may correspond to flow velocity of the gases and indicates this to be about 500 m./sec. Detonation velocity is 7700 m./sec., shock wave velocity 8500 m./sec.

velocity of a sound wave. The detonation velocity of the nitroglycerin is 7700 m./sec., whereas the initial velocity of the shock wave is 8500 m./sec. The black bands in the photograph were actually caused by black bands around the glass tube which held the nitroglycerin. These show that the detonation reactions were completed before the band was broken by the expanding gases. The nonluminous zone in the direction of film travel between the detonation wave and the luminous expanding gases apparently represents the time required for the glass tube to break, and corresponds to about five millionths of a second.

Besides giving an accurate method of measuring the velocity of the detonation wave, the rotating-drum camera may also be used for estimating its duration, that is, the time required for it to travel a distance equal to its width. The diagrammatic picture of the detonation wave shown in Fig. 1 can be very nearly duplicated photographically. If, instead of firing an explosive column at right angles to the direction of motion of the film, it is fired parallel to the film, then the

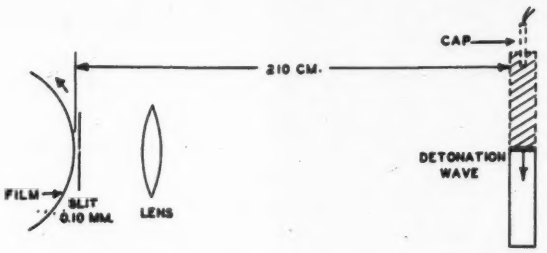

FIG. 5. PHOTOGRAPHING DETONATION WAVE. The image of the detonation wave is reversed by the lens and travels parallel to the film. Exposure time is limited by the slit width. When image speed and film speed are the same, a photograph of the detonation wave and hot gases is obtained as they pass in front of the slit.

film speed can be adjusted so that it is traveling in the same direction and at the same speed as the image of the detonation wave. It is possible, in a sense, to photograph the detonation wave in the same way as a racing car might be photographed from another racing car driven alongside. The experimental arrangement is illustrated in Fig. 5, and the resulting photograph of this type is shown in Fig. 6. This gives a picture very similar to the scheme in Fig. 1, with the exception that the gases are not only moving in the direction of the detonation wave but are also expanding outward. With especially strong confinement, actual conditions might be expected to be similar to those in the model. The flow velocity of the gases behind the detonation wave has been calculated by H. Langweiler[2] to be of the order of 1000 m./sec.

When the explosive is practically unconfined, as for example a cartridge of blasting gelatin wrapped in a thin sheet of cellulose acetate, the main features of the photographs are similar to those for nitroglycerin, but there are some differences as may be observed from Fig. 7. Because there is no confinement, the gases can start expanding immediately; hence, there is no dark zone between the detonation wave and the expanding gases. Probably the slope of the streamers

FIG. 6. DETONATION WAVE AND EXPANDING GASES FROM NITROGLYCERIN. The nitroglycerin was contained in a 30-mm. i.d. glass tube. This photograph was taken by the method diagrammed in Fig. 5. Partly detonated cartridge is sketched in to illustrate its position. Duration of luminosity in detonation zone is about 0.5 microseconds. Dark zone behind detonation wave persists for about 5 microseconds. This may correspond to a rarefaction wave. Total duration of luminosity is about 60 microseconds. Expansion of gases to about 20 cm. on each side of cartridge has occurred in this time.

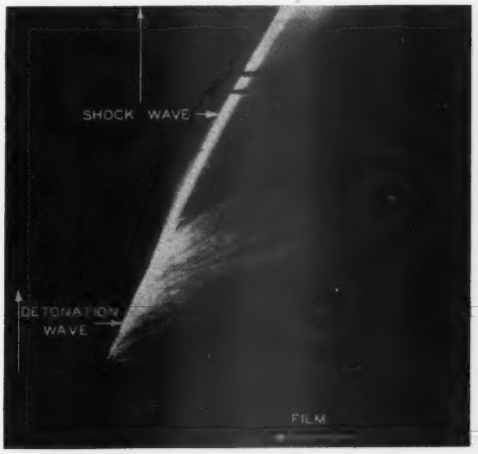

FIG. 7. DETONATION OF BLASTING GELATIN. The blasting gelatin was contained in a 31-mm. diameter cellulose acetate tube (0.1 mm. wall). Here gases start expanding immediately so there is no dark zone between detonation wave and expanding gases. Compare with Fig. 4.

moving to the right may be taken as an indication of the "flow velocity" of the gases, and this is of the order of 2000 m./sec. which is somewhat higher than calculated values. For the nitroglycerin on the other hand, the measured "flow velocity" was approximately 500 m./sec., although for a smaller diameter tube (10 mm. instead of 31 mm.).

The photograph obtained with nitroglycerin (Fig. 6) shows the gases immediately behind the detonation wave to be relatively nonluminous. This indicates that in the luminous zone associated with the detonation wave chemical reactions are taking place which give rise to the intense luminosity. The lack of luminosity immediately behind the detonation wave suggests that there is insufficient purely thermal light radiation to affect the film during the very short exposure of the film—less than one millionth of a second.

The nonluminous area might possibly be due to the rarefaction wave which Langweiler[2] has deduced should follow the detonation wave. If this dark zone actually represents a rarefaction wave, it is of interest to present Langweiler's calculated values for the temperature and pressure in the detonation and rarefaction waves, respectively.

Trinitrotoluene

Detonation Wave		*Rarefaction Wave*	
Temperature	*Pressure*	*Temperature*	*Pressure*
3100°C.	95,000 atm.	2350°C.	50,000 atm.

For TNT there is thus a marked decrease in temperature from 3100°C in the detonation wave to 2350°C in the rarefaction wave, which would account for a marked decrease in luminosity. If there is actually a rarefaction wave following immediately behind the detonation wave, this could explain the dark zone.

The rapid outward expansion of the gases behind the detonation wave in the relatively unconfined nitroglycerin (Fig. 6) results in a very rapid decrease in pressure. Thus, 10 microseconds after the passage of the detonation wave, the gases have expanded from a diameter of 3 cm. to 15 cm. and the pressure has dropped to less than 1/25 of its maximum.

The nature of impact waves, of which detonation waves and explosive shock waves are examples, is fairly well understood. They have some quite remarkable properties which include a very steep wave

front, a high velocity, and very high temperature and pressure. Becker has calculated the width of the wave front to be less than the average distance between two molecules. In a detonation wave this distance would be less than 10^{-7} cm. This amounts to a virtual discontinuity at the wave front and its width is negligible relative to the width of the whole wave which would be estimated at about 2.5 mm. from a photograph like that in Fig. 6. The temperatures and pressures in shock waves are very much higher than would be calculated from the usual laws of adiabatic compression. Also, both detonation and shock waves are followed by a high-velocity flow of gases directly behind. Data illustrating the properties of the impact wave in air as calculated by Becker[15] are shown in the following table.

Properties of Shock Wave in Air at Atmospheric Pressure and 273°K.

Velocity of Wave	*Flow Velocity of Gases Behind Wave*	*Pressure in Wave*	*Temperature in Wave According to*	
			Hydrodynamic Theory	*Adiabatic Law*
m./sec.	m./sec.	atmos.	°K.	°K.
1000	745	10	725	530
3000	6000	100	3,900	950
9000	8400	10,000	19,000	1700

If the adiabatic compression law held, the wave would be barely luminous for a velocity of 9000 m./sec. Actually the shock waves may be photographed at velocities as low as 1500–2000 m./sec. The temperature calculated according to the hydrodynamic theory is probably somewhat too high as judged by the assumptions involved in the method of calculation. Nevertheless, the intense luminosity of the waves indicates the temperature to be very high.

A side view of a shock wave produced in the air column two inches from the end of a cartridge of blasting gelatin is shown in Fig. 8. The significance of the ragged tail is not clear, but it might be associated in some way with the cellulose acetate tube in which it is traveling. The luminosity immediately preceding the wave front is probably caused by scattered light from the tube. The duration of the wave, that is, the time for it to travel a distance equal to its length, is about 0.3 microsecond, which corresponds to a length of 2.5 mm. for the luminous zone.

In liquids the temperatures which would be obtained for a shock wave are very much lower as shown by Becker's calculations for diethyl ether.

Properties of Shock Wave in Diethyl Ether at 273°K

Velocity m./sec.	*Pressure in Wave* atmos.	*Temperature in Wave According to* *Hydrodynamic Theory* °K.	*Adiabatic Law* °K.
1260	100	275	275
3000	20,000	484	396
6430	100,000	1250	620

Even at the highest velocity the temperature is so low that the shock wave would be nonluminous. Experimentally this is verified as

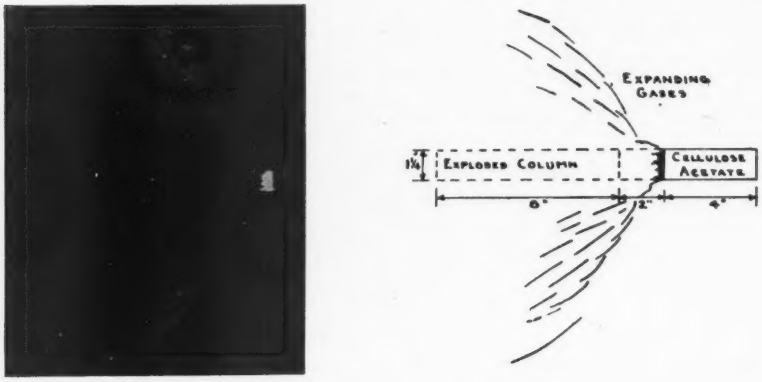

FIG. 8. SHOCK WAVE FROM BLASTING GELATIN. Photograph of shock wave two inches from end of a cartridge of blasting gelatin. Duration of shock wave is about 0.3 microseconds.

illustrated by comparison of Figs. 9 and 10. The former shows the propagation of detonation from one cartridge of blasting gelatin to another across a half-inch air gap. The second shows a similar picture but the cartridges are suspended in water. Here it is observed that no visible shock wave is produced in the liquid. Also there is no "after-burning" as it is completely quenched by the water. Fig. 11 shows even more clearly the absence of a luminous shock wave from the end of a cartridge of blasting gelatin suspended in water.

The detonation velocity of explosives can be calculated with some success from the hydrodynamic theory of detonation which was originally developed mathematically by Chapman[16] and Jouguet.[17] Its application to solid and liquid explosives has received considerable development by Becker,[15] Schmidt,[18,19] Langweiler[2] and Brown.[20] Ac-

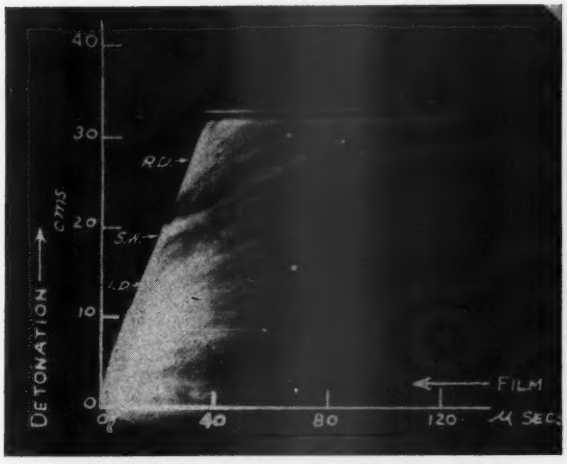

FIG. 9. PROPAGATION ACROSS AN AIR GAP. Propagation of detonation from one cartridge of blasting gelatin to another across a ½-inch air gap.

I.D. = Detonation wave for initiator cartridge
S.W. = Shock wave across gap
R.D. = Detonation wave in receiver cartridge
Detonation velocity is 7800 m./sec.

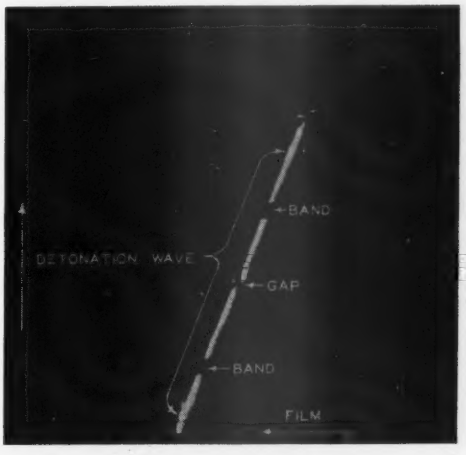

FIG. 10. PROPAGATION ACROSS WATER GAP. Propagation of detonation from one cartridge of blasting gelatin to another across a ½-inch gap in water. The shock wave is not visible in water and the flame from the expanding gases is quenched. Detonation velocity is 7800 m./sec.

cording to the approximate relations of the theory, the detonation velocity may be calculated from the following formula.

$$D = \frac{1.290 \times 10^4}{(1 - \alpha_1/V_e)}\left[\frac{(\gamma + 1)T_e}{M}\right]^{1/2} \qquad (3)$$

$$\gamma = C_p/C_v$$

α_1 = Covolume in detonation zone
T_e = Explosion temperature (See Eq. 1)
V_e = Molar volume of explosion gases
M = Molecular weight of gases

The explosion pressure and temperature are calculated for the condition that the volume of the gases is unchanged from that occupied

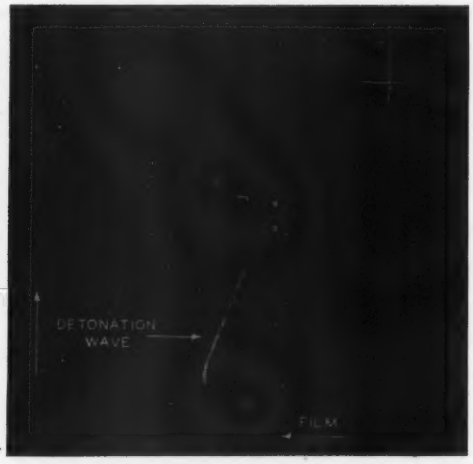

FIG. 11. DETONATION OF BLASTING GELATIN UNDER WATER. The cartridge of blasting gelatin was 1¼ by 8 in. The "after-burning" is quenched by the water and there is no visible shock wave. The black bands across the detonation wave were caused by strips of black tape wrapped around the cartridge.

by the solid or liquid which is assumed to detonate in its own volume. However, the flow of gases in the direction of the detonation wave means that the density in the wave will be greater than that in the original explosive. This compression of the gases in the detonation zone results in a higher temperature than the calculated explosion temperature and pressure.

The temperature and molar volume of the gases in the detonation zone may be calculated according to the theory from the following relationships:

$$T_1 = T_e \frac{2\gamma}{\gamma + 1}; \qquad V_1 = V_e \frac{\gamma + \alpha_1/V_e}{\gamma + 1}. \tag{4}$$

Calculation of the pressure and detonation velocity for solids and liquids requires a knowledge of the gas laws at the very high pressures and temperatures involved. For this purpose Abel's gas law seems to apply

$$P(V - \alpha) = RT \quad \text{or} \quad P = \frac{RT}{V} \cdot \frac{1}{(1 - \alpha/V)}. \tag{5}$$

The covolume, α, is the effective volume of the molecules themselves. Since at very high pressures α is no longer a constant, it is necessary to determine its value. This has been done in some cases by determining experimentally the detonation velocity of a solid explosive and then calculating back to get the covolume. On the other hand, Brown has extrapolated pressure-volume data on gases to estimate the covolume at the pressures and densities involved in the detonation zone with a fair degree of success.

On the basis of Brown's values of α, comparative detonation velocities for nitroglycerin, blasting gelatin, and 60% gelatin dynamite have been calculated.

		Detonation Velocity	
	Density	*Experimental* m./sec.	*Calculated* m./sec.
Nitroglycerin	1.59	7700	7500
Blasting Gelatin	1.60	7800	8200
60% Gelatin Dynamite	1.50	5500	6000

The agreement can be considered fairly good and should be improved as more data become available on the pressure-volume relationships at the very high pressures.

Data on the pressure, volume and temperature relationships in the detonation zone are also of interest and the calculated results are shown in the tabulation on the next page.

The very high pressures which are apparently attained in the detonation wave are especially striking.

One other aspect of the detonation wave which is of interest is the

Explosive	Pressure atmos.		Molar Volume cc./mole		Temperature °C.	
	Explosion*	Det. Wave†	Explosion*	Det. Wave†	Explosion*	Det. Wave†
Nitroglycerin	86,000	118,000	18.27	15.67	3870	4250
Blasting Gelatin	98,000	140,000	17.11	14.85	3800	4150
60% Gelatin Dynamite‡	57,000	82,000	22.15	19.0	2900	3200

* If explosion gases occupy volume of solid or liquid explosive.
† In the detonation wave.
‡ For explosive ingredients; based on Brown's[7,20] data.

shape of the detonation wave front. If the cartridge of explosive is pointed at the camera the detonation wave is not visible to the camera until it reaches the end of the cartridge. Hence a cylindrical shadow will appear on the film, as in Fig. 12, with streamers on either

FIG. 12. SHAPE OF DETONATION WAVE FRONT. A cartridge of blasting gelatin was pointed at the camera and detonated toward it. Detonation started at "1" and reached the end of the cartridge at "2". The straight edge at "2" indicates that the detonation wave has a plane wave front. The time elapsed between "1" and "2" is about 25 microseconds and represents the time for the 20 cm. length of cartridge to detonate.

side corresponding to the expanding gases. When the detonation wave reaches the end of the cartridge the luminosity developing on the film will have a straight edge if the wave front is plane or a convex edge if the wave front is convex. Thus with a convex wave the detonation reaches the end of the cartridge first in the middle and later at the edges and thus would show a curved trace on the film. A plane wave reaches the end of the cartridge at the same instant both in the middle and at the edges and thus gives a straight edge in the photograph. Fig. 12 was obtained by photographing a cartridge of blasting gelatin which was pointed at the camera. As nearly as can be determined from the picture a straight edge is produced when the detonation wave reaches the end of the cartridge, thus indicating the wave front to be plane in this high velocity explosive. In low rate explosives, however, the wave front appears to be convex.

MECHANICS OF DETONATION

While the foregoing gives a good overall picture of detonation, it does not tell very much about the mechanism of the chemical reactions involved. It was originally suggested by Berthelot that the molecular particles produced in the decomposition of the explosive molecules moved ahead of the detonation wave and activated the undecomposed molecules. This is perhaps as good a picture as we can obtain even at the present time. In support of this view, the energy of decomposition is of the order of 300,000 cal./mole for nitroglycerin and the activation energy has been estimated as being in the neighborhood of 50,000 cal./mole. While the primary products of decomposition are not known, the actual energy involved in the initial decomposition is probably so great that enough molecules would be projected forward at speeds greater than the detonation velocity to activate the explosive molecules at the wave front. The duration of the detonation wave itself appears on the basis of the author's experiments to be somewhat less than one millionth of a second for nitroglycerin. During this time at the pressures and temperatures involved, the number of collisions is of the order of ten million per molecule, which seems to be entirely adequate for equilibrium to be reached among the gaseous products.

A great deal of progress has been made both theoretically and experimentally in studies on detonation during the past fifty years. Nevertheless, more work remains to be done to put the knowledge of detonation on a thoroughly satisfactory plane.

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FREQUENCY DISCRIMINATION IN THE LOW VELOCITY ZONE*

T. R. SHUGART†

ABSTRACT

The various factors controlling the "character" of reflection seismograph records are so numerous and so complex that it is very difficult to isolate and investigate each of them experimentally. One of these factors is the frequency discrimination due to multiple reflections in the low velocity zone ("weathered layer"). With a few simplifying assumptions this problem reduces to one already treated in the classical theory of acoustics. It is shown that for a given weathering thickness the transmission is a periodic function of frequency. The ratio of the maximum to the minimum energy transmission is nearly equal to the square of the ratio of the specific acoustic impedance of the high velocity to that of the low velocity material. The phase lag due to the presence of the weathered layer is shown to be a non-linear function of the weathering thickness for any given frequency. Graphs of transmission as a function of frequency are shown for various thicknesses of the low velocity zone.

INTRODUCTION

It is the purpose of this paper to show how the frequency spectrum or "character" of a reflection seismograph record may be considerably affected by multiple reflections occurring in the low velocity zone underlying the seismic pickup.

Born and Kendall[1] have pointed out that a reflection taken from a seismograph trace can be analyzed by the use of Fourier integrals, and the relative amplitudes and phases of all its component frequencies determined. Conversely, given the amplitude and phase relationships of all the component frequencies, the resultant reflection is completely determined. It follows that changes in the relative amplitudes and phases of the frequency components of a reflection would produce corresponding changes in the character of the reflection.

The frequency spectrum of the transient waves generated by detonations in shot holes has been investigated both theoretically and experimentally by Sharpe,[2] who has found that even in the first 250 feet of its travel path, the frequency content of the waves undergoes great change. These waves are undoubtedly further altered by such factors as selective absorption, dispersion, multiple reflection and others, until the emergent reflected wave arrives at the surface of the

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[1] W. T. Born and J. M. Kendall, *Application of the Fourier integral to some geophysical instrument problems*. GEOPHYSICS, Vol. VI, No. 2, p. 105, 1941.

[2] Joseph A. Sharpe, *The production of elastic waves by explosion pressures, Part I and Part II*, GEOPHYSICS, Vol. VII, No. 2, p. 144, No. 3, p. 311, 1942.

ground with a frequency spectrum very different from that observed near the point of detonation. The emergent wave is then still further altered by the coupling of the seismic pickup to the ground[3] and by the frequency characteristic of the seismograph system itself.

The factors controlling the frequency content of a recorded reflection are thus so numerous and so complex that it is very difficult to isolate and investigate each of them experimentally. The scope of this paper is limited to a discussion from a theoretical viewpoint of just one of these factors, namely, the frequently discrimination due to multiple reflections in the low velocity zone underlying the seismic pickup.

TRANSMISSION OF ELASTIC WAVES THROUGH THREE MEDIA

Fortunately, elastic wave theory furnishes us with the means of analyzing this resonance effect in the low velocity zone. For the purpose of this analysis we assume that the surface of the ground and the base of the low velocity zone are horizontal planes separating three negligibly dissipative homogeneous elastic media of different densities and different wave velocities, namely, the air, the low velocity (sometimes called "weathered") zone, and the underlying higher velocity (or "unweathered") zone. (Although the terms "weathered" and "unweathered" are geological misnomers their use is widespread. Their use here will be confined to their geophysical meaning.) We further assume that these three media are unbounded except by the plane interfaces separating them from each other. If we now finally assume a plane simple harmonic acoustic wave moving upward normal to the interfaces, we have reduced our problem to one which has already been discussed in the literature. Stuart and Lindsay,[4] for example, give a derivation of the formula for the power transmission through three elastic media such as we have postulated.

The equations which we shall use are:

$$A_1 = \tfrac{1}{2}A_3[(r_{12}r_{23} + 1)\cos k_2W + i(r_{12} + r_{23})\sin k_2W] \qquad (1)$$

and

$$\frac{I_3}{I_1} = \frac{4r_{12}r_{23}}{(r_{12}r_{23} + 1)^2} \cdot \frac{1}{1 - \dfrac{(r_{12}^2 - 1)(r_{23}^2 - 1)}{(r_{12}r_{23} + 1)^2}\sin^2 k_2W} \qquad (2)$$

[3] Harold Washburn and Harold Wiley, *Effect of the placement of a seismometer on its response characteristics*, GEOPHYSICS, Vol. VI, No. 2, p. 116, 1941.

[4] G. W. Stewart and R. B. Lindsay, *Acoustics*, pp. 100–103. D. van Nostrand Co., New York. 1930.

where A_1 and A_3 are the complex amplitude coefficients of the wave in the unweathered material and in the air respectively, and where $r_{12}=R_2/R_1$ and $r_{23}=R_3/R_2$. R_1, R_2 and R_3 are the specific acoustic impedances of the unweathered material, weathered material, and air, respectively. $k_2=2\pi f/c_2$, where f is the frequency of the wave and c_2 is the wave velocity in the weathered material. W is the thickness of the weathered zone. I is the intensity, defined as the average rate of flow of energy per unit area normal to the direction of propagation (power transmission per unit area), and the subscripts *1* and *3* apply to the incident wave in the unweathered material and the transmitted wave in the air, respectively.

Eq. *2* then gives the power transmission through the weathered layer. The application of this equation to the present problem can be somewhat simplified by considering that R_2 is of the order of magnitude of 10^{-3}, whereas R_3 is 4.2×10^{-7}. r_{23} is therefore very much less than 1. $r_{12}r_{23}$ is also very much less than one so that to a very close approximation Eq. *2* becomes

$$\frac{I_3}{I_1}=\frac{4r_{12}r_{23}}{1+(r_{12}^2-1)\sin^2 k_2W}. \tag{3}$$

It is noted here that when $\sin^2k_2W=0$, $I_3/I_1=4r_{12}r_{23}$, and when $\sin^2k_2W=1$, $I_3/I_1=4r_{12}r_{23}/r_{12}^2$.

The energy transmission is thus minimum when $\sin^2k_2W=0$ and is maximum when $\sin^2k_2W=1$. The ratio of maximum to minimum transmission is $1/r_{12}^2$ or R_1^2/R^2_2.

Now Eq. 3 gives the transmission of energy through the low velocity zone and into the air. However, since the usual type of seismograph pickup is a velocity detector placed in contact with the surface of the ground, it is desirable to express Eq. 3 in terms of the particle velocity at the surface of the ground, rather than in terms of the intensity transmitted into the air.

The expression for the intensity of a plane wave can be written:

$$I=\tfrac{1}{2}v^2R$$

where v = the maximum particle velocity
and R = the specific acoustic resistance of the medium.
Then

$$I_3/I_1=v_3^2R_3/v_1^2R_1=r_{12}r_{23}v_3^2/v_1^2 \tag{4}$$

where the subscripts 1 and 3 refer to the wave in the unweathered material and in the air, respectively.

Combining Eqs. 3 and 4:

$$v_3^2/v_1^2 = 4/[1 + (r_{12}^2 - 1) \sin^2 k_2W]$$

and

$$v_3/v_1 = 2[1 + (r_{12}^2 - 1) \sin^2 k_2W]^{-1/2}. \quad (5)$$

Now v_3 was defined as the maximum particle velocity of the emergent wave in the air. v_3 must also be the maximum particle velocity at the earth-air interface in order that the boundary condition of continuity of displacement across the interface be satisfied.

A velocity detector with a constant frequency response placed on the surface of the ground will then have an output the amplitude of which is directly proportional to v_3. If such a detector could be used below the low velocity zone, responding only to the incident wave, its output would be directly proportional to v_1.

MAXIMA AND MINIMA OF TRANSMISSION

Eq. 5 then gives the frequency transmission of the low velocity zone in terms of recordable amplitude rather than in terms of power as in Eq. 3.

Inspection of Eq. 5 reveals:

(1) That the ratio v_3/v_1 has a minimum value of 2 corresponding to $k_2W = n\pi$ (where n is zero or any integer). Since $k_2 = 2\pi f/c_2$, this condition is satisfied when $W = nc_2/2f$, i.e., when the thickness of the low velocity zone is zero or an integral half wave length. Under this condition the transmission is independent of the properties of both the weathered and the unweathered material.

(2) That the ratio v_3/v_1 has a maximum value of $2R_1/R_2$ when $k_2W = m\pi/2$ (where m is any odd integer), i.e., when the thickness of the weathering is an odd integral quarter wavelength.

Figs. 1 through 4 are graphs showing the form of the function in Eq. 5. In these graphs, $R_1/R_2 = 4$ has been chosen as a fairly representative value. A wave velocity in the weathered layer of 2000 feet per second was used. Values of v_3/v_1 are plotted as ordinates against values of frequency as abscissae. Only the limited frequency range of from 0 to 200 cycles per second is shown as this represents the most important part of the range for ordinary seismograph recording.

Fig. 1 is for $W = 10$ feet. For this weathered layer thickness, peaks of transmission occur at 50 cycles per second and 150 cycles per

second. In Fig. 2 for $W = 15$ feet three peaks instead of two fall within the frequency range under 200 cycles. In Fig. 3 for $W = 20$ feet, four peaks are shown, and in Fig. 4 for $W = 30$ feet there are six peaks in this range. For greater values of W, the peaks will fall correspondingly closer together. Thus for $W = 80$ feet there would be 16 peaks between 0 and 200 cycles per second, or peaks 12.5 cycles apart.

The height of these peaks is completely determined by R_1 and

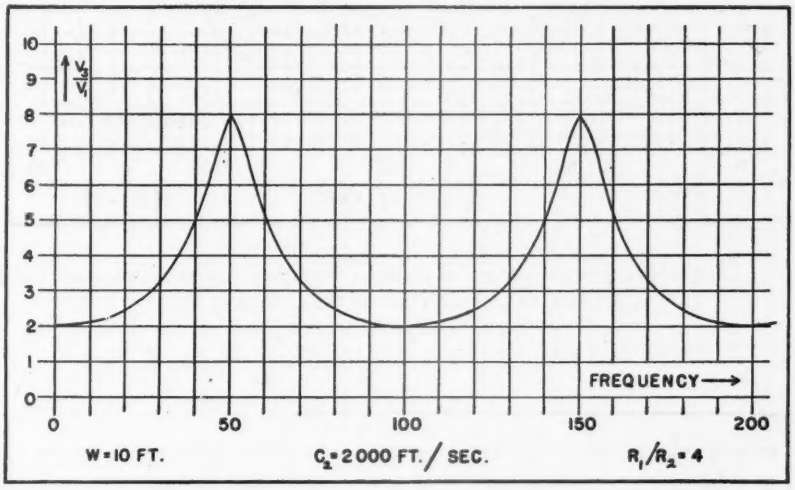

FIG. 1. Frequency transmission curve for a weathered layer thickness of ten feet. The ordinates (v_2/v_1) are the amplitude output of a velocity detector with a constant frequency response. The ratio of the acoustic resistance of the unweathered material to that of the weathered material is four.

R_2, being equal to $2R_1/R_2$. The height of the curve at the minima is always equal to 2.

The frequencies at which the peaks occur are independent of R_1 and R_2 and are completely determined by W and c_2. These frequencies are given by $mc_2/4W$, where m is any odd integer. The frequencies at which the minima occur are given by $nc_2/2W$, where n is zero or any integer.

PHASE OF TRANSMITTED WAVE

That there is a phase difference between the incident wave at the first interface and the transmitted wave at the second is obvious.

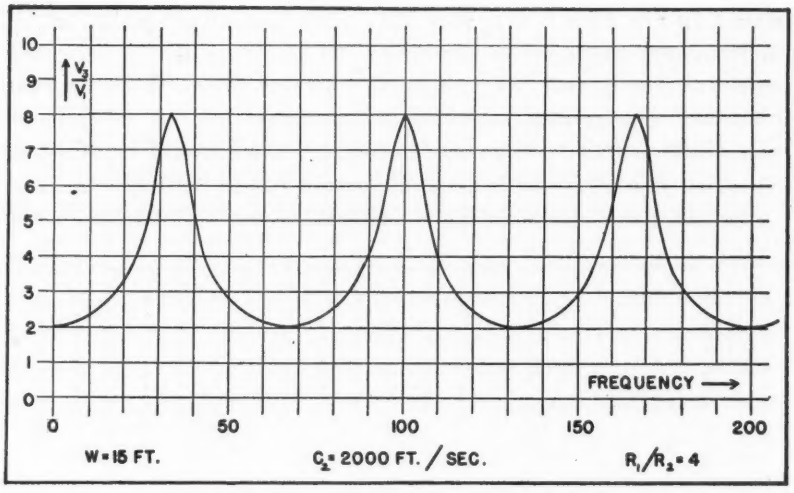

FIG. 2. Frequency transmission curve for a weathered layer thickness of fifteen feet. Other conditions are the same as in Fig. 1.

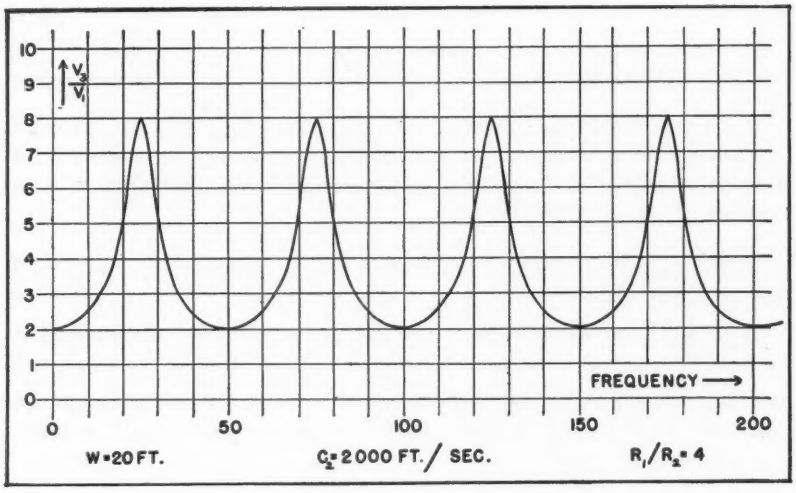

FIG. 3. Frequency transmission curve for a weathered layer thickness of twenty feet. Other conditions are the same as in Fig. 1.

Intuitively one might think that this phase difference increases linearly with W or f. We can easily show, however, that this is not generally true. If we call this phase difference θ, then we may write from Eq. 1

$$\tan \theta = \frac{(r_{12} + r_{23})}{(r_{12}r_{23} + 1)} \tan k_2 W.$$

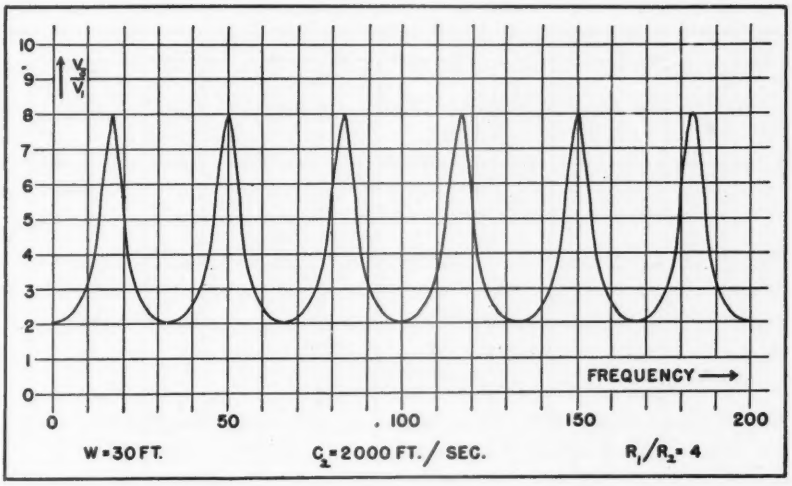

FIG. 4. Frequency transmission curve for a weathered layer thickness of thirty feet. Other conditions are the same as in Fig. 1.

Remembering that $r_{23} << r_{12}$ and $r_{12}r_{23} << 1$, the above equation becomes, to a close approximation

$$\tan \theta = r_{12} \tan k_2 W = (R_2/R_1) \tan k_2 W = (R_2/R_1) \tan 2\pi W/\lambda \quad (6)$$

where λ is the wavelength in the weathered layer.[5]

In Fig. 5, Eq. 6 is plotted with θ as ordinates and W/λ as abscissae. This interesting curve shows that the rate of increase of θ with W and f is greatest where W is an odd integral quarter wavelength and is least where W is zero or an integral half wavelength. Note that the phase change is most rapid near the resonance peaks and least rapid near the non-resonant valleys in Figs. 1 to 4.

[5] For a more comprehensive discussion of the time delay in the weathered layer as a function of frequency see Alfred Wolf *The time delay of a wave group in the weathered layer*, GEOPHYSICS, Vol. V, No. 4, pps. 367–372 (Oct., 1940).

SUMMARY

The foregoing theoretical considerations give a quantitative analysis of the frequency discrimination due to transmission through the low velocity zone. It does not, however, explain the mechanics of how this discrimination is accomplished in a way that is easy to visualize. What happens, briefly, is this: A sinusoidal wave is pro-

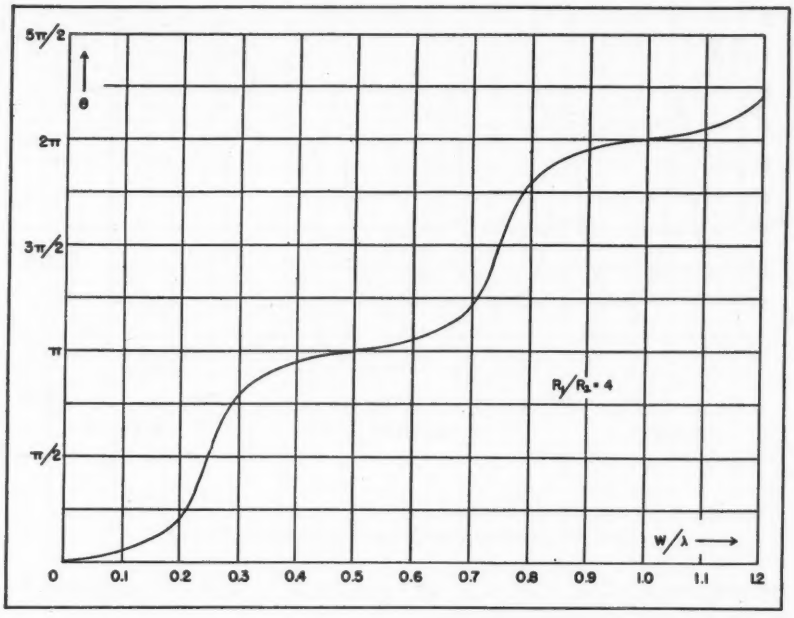

FIG. 5. Phase angle, θ, between the incident wave at the base of the weathered layer and the transmitted wave at the surface of the ground, plotted as ordinates, against W (weathered layer thickness) over λ (wavelength in weathered layer) as abscissae. Note that this curve has its steepest slopes at $W/\lambda=0.25$, $W/\lambda=0.75$ etc. W/λ has this same series of values at the various resonance peaks of Fig. 1 through Fig. 4.

gressing upward in the unweathered material. As a cycle of this wave reaches the interface to the low velocity zone, part of its energy is reflected back downward and is lost. Part, however, is transmitted into the low velocity zone where it continues upward until it reaches the interface at the surface of the ground. Here a small part of its energy is transmitted into the air but most of its energy is reflected back downward (with a change of phase of π radians). This reflected

energy now moves downward to the base of the low velocity zone where a part of it is transmitted downward into the unweathered material and is lost, and a part is reflected back upward into the low velocity zone again (this time without change of phase). Now if this twice reflected energy is in phase with the energy just emerging into the low velocity zone from the unweathered material, the resultant amplitude is greater than that of the emergent wave alone. This reinforced energy is again twice reflected and again reinforces the emergent wave in the low velocity zone. As this cycle of reflections repeats itself at the top and bottom of the low velocity zone, we have simply a case of mechanical resonance, i.e., of standing waves in the low velocity zone. It is only for certain frequencies that this will occur and these are the frequencies at which the peaks in the figure are shown.

In all of the analysis so far only simple harmonic waves have been considered. Application of these results quantitatively to transients can be done by making appropriate use of Fourier integrals, although this is beyond the scope of this paper. It will suffice to point out again that the transient can be considered to be composed of a spectrum of simple harmonic waves of all frequencies. Any alteration in this spectrum produces an alteration in the character of the transient.

The frequency spectrum of the transient arriving at the surface of the ground is different from that of the transient arriving at the base of the low velocity zone, this difference being determined by the resonance characteristic of the low velocity zone. It follows therefore that the frequency spectrum or reflection character of a reflection record is altered by changes in weathering thickness, all other factors being equal.

Referring again to Figs. 1 to 4, it is at first surprising that amplitude transmission ratios of four to one exist. Such ratios might be expected to produce much more violent character changes than are actually observed for changes in the thickness of the low velocity zone. This is accounted for in part by the fact that the seismograph itself usually has a relatively limited and somewhat peaked frequency response. Some question should also be raised as to the validity of the fundamental assumptions used in the derivation of the power transmission equation (Eq. 2). For example, the three transmitting media may be separated by zones of intermediate velocities rather than by plane interfaces. Also the effects of absorption and dispersion were completely neglected. Any of these factors if present would tend to

flatten the resonance peaks and thus minimize the frequency discrimination.

It should also be brought out that this type of frequency discrimination need not be confined to the low velocity zone at the surface. Multiple reflection can produce frequency discrimination anywhere that the physical conditions are appropriate along the travel path of a seismic wave.

To summarize, it may be said that the frequency spectrum (or the character) of a reflection record may be considerably changed by a change in the thickness of the low velocity zone, all other factors remaining the same. Such frequencies will be emphasized as make the weathered thickness equal to an odd integral quarter wavelength. This frequency discrimination is superimposed upon the frequency spectrum generated by the detonation and subsequently altered by many other factors.

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THE EQUATION OF MOTION OF A GEOPHONE ON THE SURFACE OF AN ELASTIC EARTH*

ALFRED WOLF†

ABSTRACT

The motion of a geophone case placed on the surface of an elastic earth does not follow faithfully the motion of the earth at high frequencies. In effect, a weight placed on the surface of an elastic solid constitutes a damped oscillating system. The elastic restoring forces are determined by the area of contact between the weight and the surface of the solid and by the elastic moduli of the solid. The damping force is due to emission of elastic waves by the oscillating weight. The motion of the solid also contributes to the inertia of the system. Equations are developed for these forces on the assumption that the wave length is long compared to the linear dimensions of the area of contact between the weight and the elastic solid. This leads to a determination of the frequency of oscillation and of the decrement of such a system.

It has been recognized for some time that the motion of the case of a geophone resting on the surface of the earth is not the same as the motion of the earth undisturbed by the geophone case.[1,2] It is evident that if the surface of the earth represented the boundary of an infinitely rigid body, the motion of the geophone case and the motion of the ground in seismic prospecting would be identical. But since the values of the elastic moduli of surface material at most locations are very low, the geophone motion must differ appreciably from the motion of the ground. Even a casual consideration of the problem reveals that it is possible to regard a geophone on an elastic earth as a simple damped oscillator. The elastic restoring forces are determined by the elastic moduli of the earth on which the geophone is placed, the damping is caused by radiation of elastic waves into the earth, and the inertia is given by the mass of the geophone to which must be added a term which is due to the motion of the ground. The reaction of a system of this kind towards incident elastic waves resembles that of a low pass filter. For low frequencies, the motion of the geophone case will follow exactly the motion of the ground; at frequencies higher than the frequency of the oscillating system, the motion will be greatly reduced.

In the following paper, an attempt will be made at a mathematical

* Manuscript received August 21, 1943.

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[1] W. T. Born and A. Wolf. *The motion of a geophone on the surface of an elastic earth.* Presented at the mid-year meeting of the Society of Exploration Geophysicists, November 20, 1937.

[2] Harold Washburn and Harold Wiley. GEOPHYSICS, Vol. VI, p. 116, (April 1941).

formulation of this problem under certain simplifying assumptions. Thus, the earth will be regarded as a homogeneous elastic solid, and the geophone is supposed to be in the form of a cylindrical weight with a circular base which is in intimate contact with the surface of the solid. The elastic displacements in the solid are assumed to be free in the horizontal direction under the geophone base. Hence, the tangential stress vanishes at all points on the surface of the elastic solid. It is desired to determine the equations of motion of free oscillations of such a system when the wave length of the emitted radiation is long compared to the circumference of the geophone; this condition is satisfied when the mass of the geophone is sufficiently great. It will be assumed that the rigidity of the geophone is great compared to the rigidity of the elastic solid. Further, in order to obtain definite numerical results, it will be assumed that Poisson's ratio for the material of the elastic solid earth is 0.25.

The procedure to be employed is the following: A certain distribution of vertical stress, which is a harmonic function of time, is assumed on the surface of the solid, and it is shown that it corresponds to a surface displacement approximately constant—to second order terms —over the area of contact between the cylindrical weight and the elastic solid. The total force is then replaced by the inertia of the weight, and the quantity $j\omega(j=\sqrt{-1})$ by the differential operation d/dt; this leads to the equation of motion. It is assumed that the displacement of the weight is equal to the average displacement produced by the assumed distribution of stress on the surface of the solid. The equation thus obtained corresponds to damped harmonic motion. First order terms in the ratio of circumference of the cylinder to wave length give the damping term in the equation of motion; second order terms determine a correction to be added to the mass of the cylindrical weight to take into account the inertia of the material of the elastic solid which is moving together with the weight.

A cylindrical coordinate system will be employed, with its origin at the surface of the elastic solid in the center of the circular base of the weight. We assume the stress distribution on the surface

$$T_{rz} = 0$$

$$T_{zz} = -\frac{R}{2\pi b\sqrt{b^2 - r^2}} \quad \text{for} \quad r < b$$

$$T_{zz} = 0 \qquad\qquad\quad \text{for} \quad r \geqq b$$

where b is the radius of the cylindrical weight, R is the total force. This can be written[3]

$$T_{zz} = -\frac{R}{2\pi b}\int_0^\infty \sin yb \cdot J_0(yr) \cdot dy. \tag{1}$$

The exponential time factor $\exp(j\omega t)$ is omitted to simplify the writing of the equations.

According to the work of Lamb,[4] the vertical displacement w, positive downward, corresponding to this stress distribution, can be written

$$w = -\frac{R}{2\pi b\mu}\int_0^\infty \frac{k^2\alpha}{F(y)} \sin yb \cdot J_0(yr) \cdot dy \tag{2}$$

where y = variable of integration

$F(y) = (2y^2 - k^2)^2 - 4y^2\alpha\beta$

$\alpha = \sqrt{y^2 - h^2}$

$\beta = \sqrt{y^2 - k^2}$

$h = \omega/V$

$k^2 = 3h^2$ (assuming Poisson's ratio = 0.25)

$\omega = 2\pi f$

f = frequency

$\mu = (1/3)\rho V^2$ = rigidity

ρ = density of the elastic solid

V = velocity of longitudinal waves in the solid

b = radius of the cylinder

$R = R\exp(j\omega t)$ = total applied force

The path of integration consists of the real axis and of small semicircles above the real axis which exclude the singular points of the integrand. The square roots are positive when $y > R$. They are obtained by analytic continuation on the remaining part of the path of integration.

Substituting

$$y = hx \qquad bh = u \qquad rh = v$$

we obtain after an easy transformation

$$w = \frac{3R}{16\pi b\mu}\left[\int_0^\infty dx \frac{\sin ux}{\sqrt{x^2 - 1}} J_0(vx) \frac{8(2x^2 - 3)^2(x^2 - 1)}{g(x)}\right.$$

$$\left. + \int_0^\infty dx \frac{\sin ux}{\sqrt{x^2 - 3}} J_0(vx) \frac{32x^2(x^2 - 1)(x^2 - 3)}{g(x)}\right] \tag{3}$$

[3] Cf. Gray, Mathews, McRobert: Bessel Functions. p. 65.

[4] Lamb. Phil. Trans. Roy. Soc. *203*, 1904.

with

$$g(x) = 32x^6 - 168x^4 + 216x^2 - 81$$
$$= [x^2 - \tfrac{3}{4}][x^2 - \tfrac{3}{4}(3 + \sqrt{3})][x^2 - \tfrac{3}{4}(3 - \sqrt{3})].$$

In the second integral $\sqrt{3}x$ is used in place of x for a variable of integration; further, the integrands are expanded in partial fractions, and this leads to the type of integral evaluated in the Appendix. The development is in powers of the small quantities $u=bh$ which is the ratio of the circumference of the cylinder to the wave length and of $v=rh$. We thus obtain, for $r<b$,

$$w = \frac{9R}{16b\rho V^2}\left[1 - 1.3666\,\frac{b}{V}\cdot j\omega + \frac{9}{8}\,\frac{b^2 + r^2/2}{V^2}\,(j\omega)^2\right] \qquad (4)$$

to second order in bh and rh. It is seen that the displacement is constant except for second order terms. Averaging over the area of the circle $r<b$

$$w = \frac{9R}{16b\rho V^2}\left[1 - 1.3666\,\frac{b}{V}\cdot j\omega + 1.4062\,\frac{b^2}{V^2}\,(j\omega)^2\right]. \qquad (5)$$

The next step is to express R in terms of w, expand to second order terms in $j\omega$, and replace $j\omega$ by the operator d/dt. It follows that

$$R = -M\ddot{w} = \frac{16}{9}\,b\rho V^2\left[1 + 1.3666\,\frac{b}{V}\,\frac{d}{dt} + 0.4613\,\frac{b^2}{V^2}\,\frac{d^2}{dt^2}\right]w, \qquad (6)$$

where M is the mass of the cylindrical weight. The equation of motion becomes

$$(M + 0.820\rho b^3)\ddot{w} + 2.430\rho b^2 V\dot{w} + 1.778\rho b V^2 w = 0. \qquad (7)$$

The term $0.820\rho b^3$ is the mass correction, $2.430\rho b^2 V\dot{w}$ the damping force, and $1.778\pi b V^2 w$ the elastic force.

It is possible to show from the foregoing that if a harmonic force of amplitude R acts on the surface of an elastic solid, the average power emitted in the form of elastic waves is

$$0.384\,\frac{\omega^2 R^2}{\rho V^3}.$$

The same result can be obtained directly by following the methods used by Lamb in the case of a force acting on a point in an infinite medium. Incidentally, the calculation shows that 68% of the radiation is in the form of Rayleigh waves.

From Eq. 7 we deduce easily

$$f = 0.212V\sqrt{\rho b(1 - h^2)/M_1} \tag{8}$$

$$h = 0.911\sqrt{\rho b^3/M_1} \tag{9}$$

where f = frequency of oscillation
h = damping factor
$M_1 = M + 0.820\rho b^3$

It is necessary for the validity of the theory that $M >> \rho b^3$. The static force corresponding to a displacement w of the geophone is, according to Eq. 6, $(16/9)b\rho V^2 w$, which is the same as given in the literature.[5]

It is difficult to make any statement on the validity of the results obtained when applied to observations made under field conditions which differ greatly from those postulated. The most serious is the variation in the elastic properties of the earth near the surface, and its effects cannot even be estimated. The other assumption introduced in this paper is that of zero tangential stress $-T_{rz}=0-$ under the geophone base. This is not entirely correct but its effect should be small compared to the other major assumption of perfect contact between the geophone and the ground.

The theory presented in this paper may be compared with the experimental results of Washburn and Wiley,[2] but only qualitative agreement should be expected. Referring to Table I, which is reproduced from the paper of Washburn and Wiley, it is possible to compute the velocity from their data on the resonant frequency f_0. For

TABLE I. RESPONSE PEAK FREQUENCY AND AMPLITUDE FOR DIFFERENT TYPES OF GROUND

Surface	f_0 *in cps.*	*Peak Amplitude*
1. Pure Dry Sand	130	2.0
2. Dry Black Gumbo	125	1.7
3. Dry Sandy Clay (plowed)	67	2.9
4. Hard Grassy Ground	200	3.1
5. Dry Sandy Clay Loam	90 to 130	2.5
6. Damp Sticky Gumbo (plowed)	68 to 93	1.6
7. Wet Sandy Mud	61 to 80	2.2
8. Very Wet Sandy Mud	48 to 65	4.6 to 1.8
9. Wet Spongy Loam	70	2.4
10. Asphalt Road	470	1.9

Geophone weight 11 lbs., base area 14 sq. in.

[5] Frank-Mises. *Differential u. Integralgleichungen d. Mechanik u. Physik*, vol. 2, 1927 pp. 669–674.

this purpose, Eq. 8 should be employed. Assuming the density of the ground $\rho = 1.6$ g/cm^3, we find that this velocity varies between 175 ft/sec. and 750 ft/sec. for the surfaces tabulated with the exception of the asphalt road; these are reasonable values. The peak amplitude of Table I is given by the expression

$$\frac{(1 + 3h^2)^{1/2}}{2h}$$

where h is the damping factor which can be obtained from Eq. (9). The result is the computed value 2.6 of peak amplitude compared to the observed values ranging from 1.7 to 4.6. The calculated value of the damping factor in these experiments is $h = 0.22$.

APPENDIX

It is desired to calculate the integral

$$I = \int_0^\infty \frac{\sin ux \cdot dx}{(x^2 - \alpha^2)\sqrt{x^2 - 1}}$$

to second powers of the small quantity $u (u << 1)$. Since the upper limit of the integral is infinity, it is not permissible to develop *sin ux* in powers of *ux*. The procedure is the following: Consider

$$K = \int_{-\infty}^\infty \frac{\exp (jux) dx}{(x^2 - \alpha^2)\sqrt{x^2 - 1}}$$

on a path of integration which consists of the real axis and of semicircles above the real axis which surround the singularities of the integrand $(\pm\alpha, \pm 1)$. $K = 0$ because the integrand vanishes at infinity in the upper half-plane. When the sign of $\sqrt{x^2 - 1}$ is properly taken into consideration, it is seen that I can be expressed as the sum of two integrals

$$\int_0^1 \frac{\sin ux \cdot dx}{(x^2 - \alpha^2)\sqrt{x^2 - 1}} \quad \text{and} \quad \int_0^1 \frac{\cos ux \cdot dx}{(x^2 - \alpha^2)\sqrt{x^2 - 1}}$$

and an exponential (if $\alpha^2 < 1$ the principal values of these integrals must be taken). Since the limits in these are finite, *sin ux*, *cos ux* can be developed in powers of *ux*.

The integral

$$L = \int_0^\infty \frac{\sin ux \cdot J_0(vx) \cdot dx}{(x^2 - \alpha^2)\sqrt{x^2 - 1}}$$

is evaluated in a similar manner. First, $J_0(vx)$ is replaced by

$$\frac{2}{\pi}\int_0^1 \frac{\cos vx\sigma \cdot d\sigma}{\sqrt{1-\sigma^2}}.$$

The order of integration is then inverted, and use is made of

$$\sin ux \cdot \cos \sigma vx = \tfrac{1}{2}\sin (u+\sigma v)x + \tfrac{1}{2}\sin (u-\sigma v)x$$

The rest of the procedure is the same as for the Integral I.

The results are $(v<u)$:

$$L = \frac{-ju}{\sqrt{\alpha^2-1}}\tan^{-1}\sqrt{\alpha^2-1} - \frac{\pi}{4}(u^2+\tfrac{1}{2}v^2) \qquad \text{for} \quad \alpha^2 > 1$$

$$L = \frac{-ju}{\sqrt{1-\alpha^2}}\log\frac{1+\sqrt{1-\alpha^2}}{|\alpha|} - \frac{\pi}{4}(u^2+\tfrac{1}{2}v^2) \quad \text{for} \quad \alpha^2 < 1$$

to second order in the small quantities u, v. Similarly

$$M = \int_0^\infty \frac{\sin ux \cdot J_0(vx)\cdot dx}{\sqrt{x^2-1}} = \frac{\pi}{2} - ju - \frac{\pi}{8}(u^2+\tfrac{1}{2}v^2)$$

to second order in u and v.

SAND AND GRAVEL PROSPECTING BY THE EARTH RESISTIVITY METHOD*

STANLEY W. WILCOX†

ABSTRACT

The four electrode earth-resistivity method is applied to the search for sand and gravel deposits in the glaciated areas of the United States. This technique differentiates between clays and granular materials enabling the prospector to outline and roughly estimate the quantities of each without test pits or bore holes. Several examples of field surveys are given.

Shallow investigations with the Gish-Rooney four electrode earth-resistivity method are very useful for predicting the material classification of subsoils. One specific application with which the author has had some experience during the years of 1933 to 1936 concerns sand and gravel prospecting. The conventional method of locating sand and gravel deposits for civil engineering projects, especially in the glaciated areas of the United States, is to auger or test pit likely locations. This involves many negative tests, as the geologic criteria for the occurrence of this material are often elusive and misleading. For example, in the terminal moraines of Southern Minnesota and Northern Iowa the low lying hills do contain sand and gravel deposits of commercial importance buried in clay till. However, they are infrequent and require the digging out of many barren knolls to find one that is productive.

Such a problem is ideally suited to electrical prospecting. The engineer with portable earth resistivity equipment need only ground his electrodes in a favorable looking knoll and take a reading. If the apparent resistivity value for a 20 foot electrode interval is less than 200 ohm-feet, he can be almost certain that no appreciable quantity of either sand or gravel exists below his electrodes at a depth shallow enough to justify commercial excavation. For readings over 500 ohm-feet the prospect has possibilities which warrant further investigation by extending the observations along a step traverse. (A step traverse consists in progressively moving the electrodes forward, retaining a constant separation between the electrodes, so as to obtain a resistivity profile.) In this manner the areal extent of the deposit can be quickly determined. In an open field with suitable equipment and one assistant, an observer can average one set-up per minute, or run 1000 or more feet of traverse per hour.

* Manuscript received September 3, 1943.

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The summer-time specific resistivity values for a clay section above the water table in the glaciated areas of Northern United States range from 50 to 200 ohm-feet. For a sand or gravel without cover the resistivity values under similar conditions range from 1000 to 20,000 or more ohm-feet depending on its origin, degree of weathering, clay inclusions, moisture content, etc. Since the apparent resistivity values observed in the field depend on the distribution and kind of materials in the effective volume below the electrode configuration, certain generalizations can be made for their interpretation. A low apparent resistivity reading greater than the normal specific resistivity of clay indicates either a thick clay mantle overlaying sand and gravel, or a deposit of granular material with little cover intermixed with clay, or a thin deposit of clean granular material underlain with a clay bed or the water table. Changing the electrode spacing will generally eliminate one or two of these possibilities. The point of interest is that all these possibilities add up to the same thing—a poor commercial discovery; therefore, an arbitrary minimum resistivity value will satisfactorily outline an exploitable deposit. This generalization is based on several thousand resistivity readings taken over more than three hundred sand and gravel deposits where surveys were run to obtain preliminary estimates of stripping and material quantities.

After a prospect has been electrically surveyed, test pitting is done to determine the classification of the material and provide samples for laboratory analysis. These tests are located in accordance with the findings of the equi-resistivity contour map and provide good control for its interpretation. Expensive hand labor digging is held to a minimum. Less than 3 per cent of all the test pits failed to verify the resistivity predictions and these were borderline cases.

One of the most interesting surveys with this technique was carried out in the Red River Valley of North Dakota and Minnesota. Here the terrain is very flat and underlain with a thick clay or gumbo derived from the bottom deposits of ancient Lake Agassiz. With the exception of a series of beach bars many miles from the river only one commercial deposit of gravel had been found in the valley before the survey was undertaken, and that located in the bottom of the river. Scouting along the river banks revealed at a point several miles below this deposit a small showing of gravel at the water level. A resistivity survey on the plain adjacent to this outcrop mapped a north-west south-east tending resistivity "high" which could be traced for several hundred yards on either side of the river. Excavation verified that a

pre-Wisconsin gravel train had been discovered containing several tens of thousands of yards of high grade sand and gravel.

The minimum clay overburden was six feet thick which gave an apparent resistivity reading of 800 ohm-feet for a 20 foot electrode spacing. The average negative reading for the area was 80 ohm-feet. Before this discovery similar material had to be hauled more than 50 miles to build and maintain the roads in the vicinity. Needless to say, this and other subsequent geophysical discoveries ended the monopoly enjoyed by the only commercial gravel deposit in an area of several hundred square miles.

The earth-resistivity method cannot differentiate between sand and gravel. The borderline between low and high electrically resistant soils is in the silt-loess zone. Silt, wet or dry, is generally relatively quite resistant while loess can seldom be distinguished from clay. This observation is not surprising since particle size more than chemical composition seems to be the determining factor. Colloids, as would be expected, are good conductors. This fact is very important to the highway engineer who must use large quantities of porous subgrade fill which will resist frost boils and heaving. An electrically resistant non-colloidal material almost always fulfills this specification.

A few representative surveys from the files of the Minnesota State Highway Department will now be described.

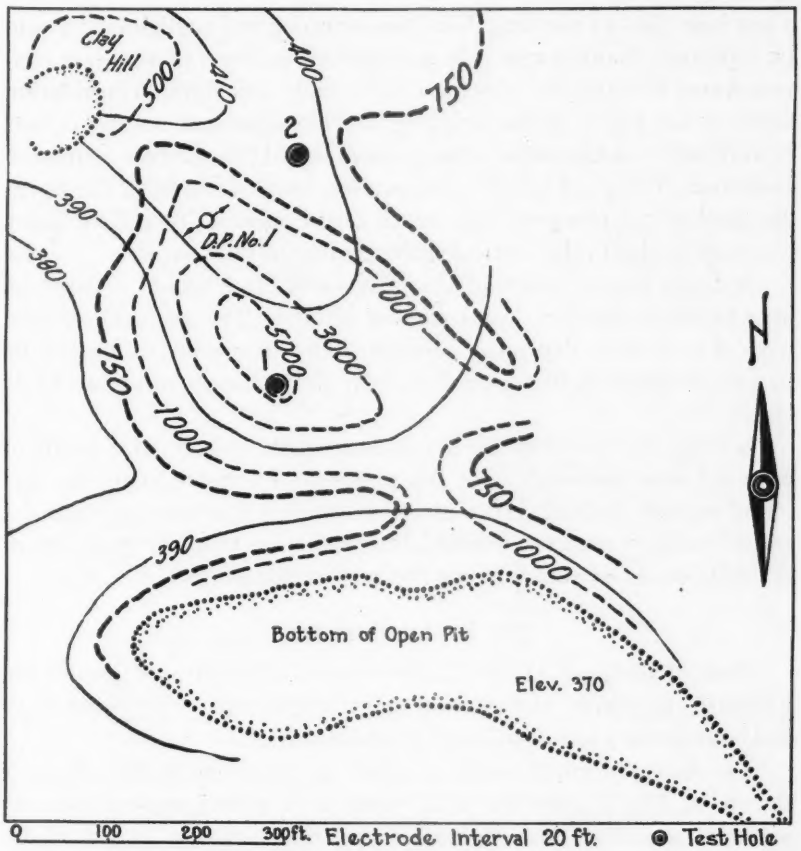
THE WASECA PROSPECT

The Waseca Survey was one of the first attempted in which the geophysical method was used for estimating quantities, and as subsequent excavation checked the method, a description of it should be of interest. (Fig. 1)

This hill is part of the terminal moraine of the Wisconsin Ice Sheet. The material is composed of sandy tills rather poorly sorted and found in large pockets surrounded by glacial clays.

The survey problem was, first, to determine if the desired quantity of sand could be found in one continuous deposit, and second, to determine the ratio of the clayey stripping to the sand below. This information could of course be obtained by a network of test holes; a slow and difficult task as the top soil was frozen and the sand tended to cave when without support. Since the grading of the sand in the pit was satisfactory, it appeared that the geophysical survey would furnish the information with only two test holes for control.

At the point where the resistance values reached 5000 ohm-feet



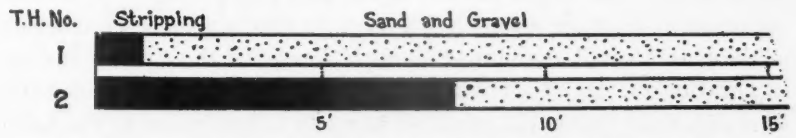


FIG. 1. Wauseca Prospect. Electrode interval is 20 feet. Solid lines are topographic contours, dashed lines are equiresistivity contours. The heavy dashed line is the resistivity contour marking the practical working limit of the deposit. In the logs of the test holes black indicates stripping, dots sand and gravel, 45° hatchuring clay, and horizontal hatchuring the water table. Following approximate correlation of resistivity to depth of stripping was made:

Resistivity, ohm-feet	*Depth, feet*
5000	1.0
3000	2.5
2000	4.0
1000	7.0
750	8.0 or more

a test hole (No. 1) was dug. Here the stripping was negligible as would be expected. Another test hole was spotted on the 750 ohm-feet contour where the stripping was found to be eight feet thick. A correlation between the depth of the stripping and the apparent resistance was established from theoretical considerations and the yardage estimated therefrom. The 750 ohm-feet contour was used to establish the working limit of the prospect. The depth of the sand in Test Hole No. 1 was used to obtain the vertical thickness for the sand lense.

A depth profile indicated that the water table was at a depth at least twice that used in the estimate of material. The practical working base of a moraine deposit is generally the water table which can be measured either by depth profiles or by projection from known table levels.

Several months after the survey was made 56,000 cubic yards of material were removed from the prospect. Excessive stripping was found outside the limit established by the electrical survey, while the actual yardage removed verified the prediction that the quantity of material would be sufficient for the engineering project.

THE WILLMAR PROJECT

West of Willmar, Minnesota in an area of ground moraines of the Keewatin Ice Sheet, the subsoils are predominantly weathered clays and contain very few deposits of granular material.[1]

The weak terminal moraine a few miles north of the prospect shown on Fig. 2 contains small pockets of poorly sorted granular materials, and leads one to believe that remnant sand or gravel deposits should exist in the vicinity of the area under investigation since the regional drainage is in this direction. In the upper left hand corner of the plan a small abandoned sand pit furnished the clue for further exploration of the adjacent area. A slight ridge runs in a southerly direction away from this pit, misleading to a prospector in the habit of associating sand or gravel with topography. Four step-traverse lines using a twenty foot electrode interval, and run one hundred feet apart, furnished the data for constructing the equi-resistivity plan.

The test holes were spotted within the area outlined by the geophysical survey. Test Hole No. 7 revealed no material and served to check the negative data. It appears that the area within the 1,000 ohm-feet contour contains about all that remains of an ancient stream

[1] Frank Leverett, *Quaternary Geology of Minnesota and Parts of Adjacent States.* Professional Paper 161, Plate 2, U. S. Geological Survey.

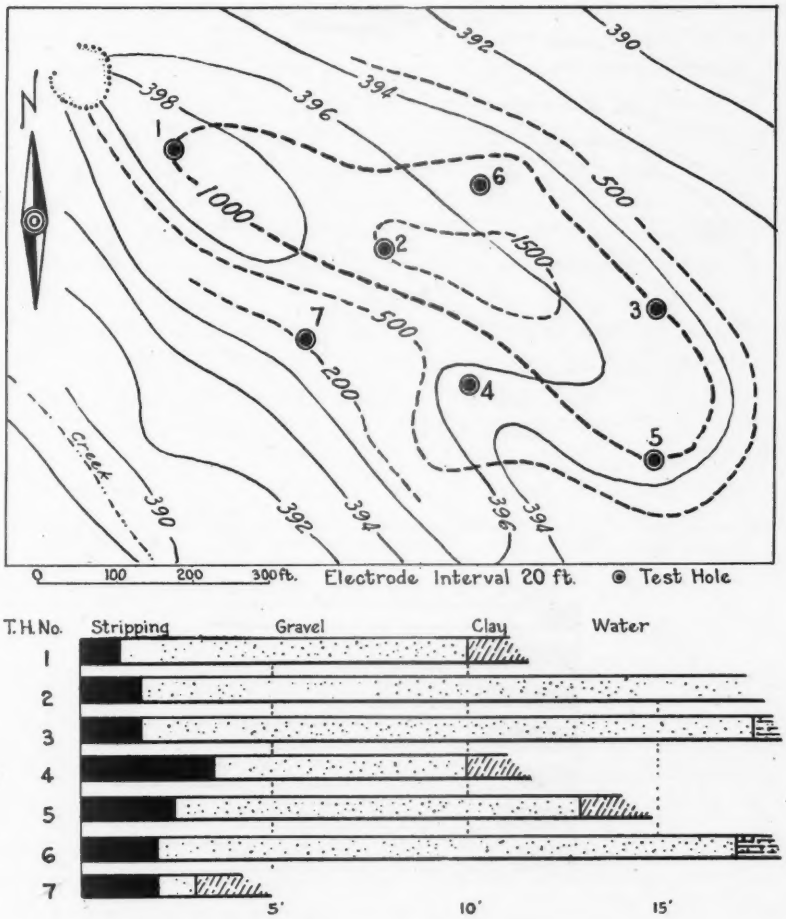


FIG. 2. Willmar Prospect. Electrode interval is 20 feet. See Fig. 1 for notation.

channel deposit, since no further extension could be found along the trend except for a very small indication one-half mile north-west of the pit. The prospect contains an estimated 35,000 cubic yards of sand and gravel.

The important feature of this survey is that there was nothing except a small sand pit as the clue that more material could be found. The topography is misleading and test holes spotted on that criterion would have condemned the area.

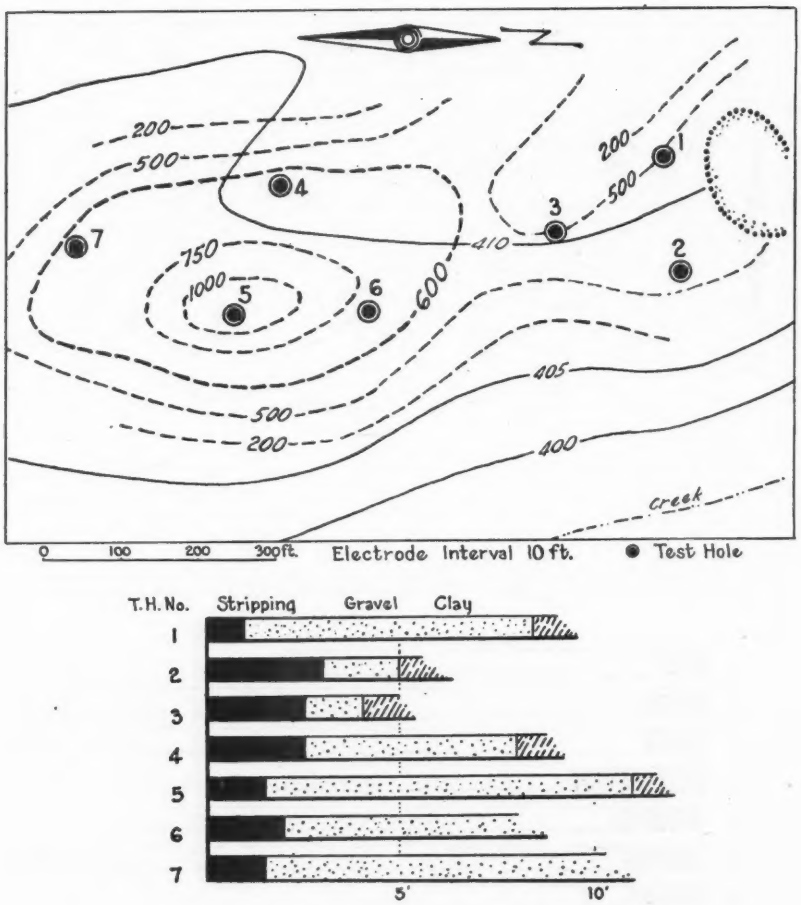


FIG. 3. Raymond Prospect. Electrode interval is 10 feet. See Figure 1 for notation.

The rapidity of the geophysical method for locating new deposits of sand and gravel makes a very creditable showing when compared with the easiest possible hand digging method. In fact, the time necessary to map the entire area of this prospect was less than that needed to auger one deep test hole such as No. 2. An observer and a helper were used to operate the earth-resistivity apparatus.

THE RAYMOND PROSPECT

Fig. 3 represents an interesting survey. The gravel side walls of the excavated area along with favorable topographic location made it

appear that a usable deposit should exist adjacent to this pit. The electrical data indicated a small extension to the south with no more material of value around it elsewhere. This information was verified by test holes. Finally an area some distance south of the pit was gridded by step-traverses and a resistivity "high" outlined. This resistance anomaly is relatively small because the earth section was very wet at the time the survey was made. Within the 600 ohm-feet contour a good quality gravel deposit was found. Several holes were dug in the marginal zone of 500–600 ohm-feet where no material worthy of excavation existed.

The fact that usable sand or gravel has never been found above the water table for readings of less than 500 ohm-feet makes the negative indications reliable, and especially so when clays have a specific resistivity of only 100–200 ohm-feet. Apparent resistivity values of less than 500 ohm-feet for a ten-foot or greater electrode interval, when the water table is not near the surface, means that the stripping is excessive, that the deposit is full of clay lenses, or that the deposit is very thin. Sand and gravel under water will show a four to one or greater ratio in apparent resistivity relative to that of clays.

THE ROCK COUNTY PROSPECT

The prospect shown on Fig. 4 contains a deposit of badly weathered sandy till of Kansan age. The resistivity values are low because of the clayey streaks throughout the sand lense. Notice the lack of symmetry between the surface and the equi-resistivity contours indicating a displacement in the location of the deposit with respect to the topography. This prospect has been opened, and the excavation demonstrated the correctness of the "electrical outline," as no appreciable sand was found beyond the limits shown on the plan.

The three field examples last mentioned are primarily qualitative surveys for the location of material. If nothing further in the way of information could be obtained by the geophysical method, it would still be valuable for the saving in useless test holes and for demonstrating continuity of material. However, it is often possible to obtain quantitative information about the prospect which is of considerable importance. The Waseca Prospect of Fig. 1 and the following example illustrate this point.

THE LUVERNE PROSPECT

At the conclusion of the last glacial epoch the impounded water found outlets through the moraine front and started rapidly flowing

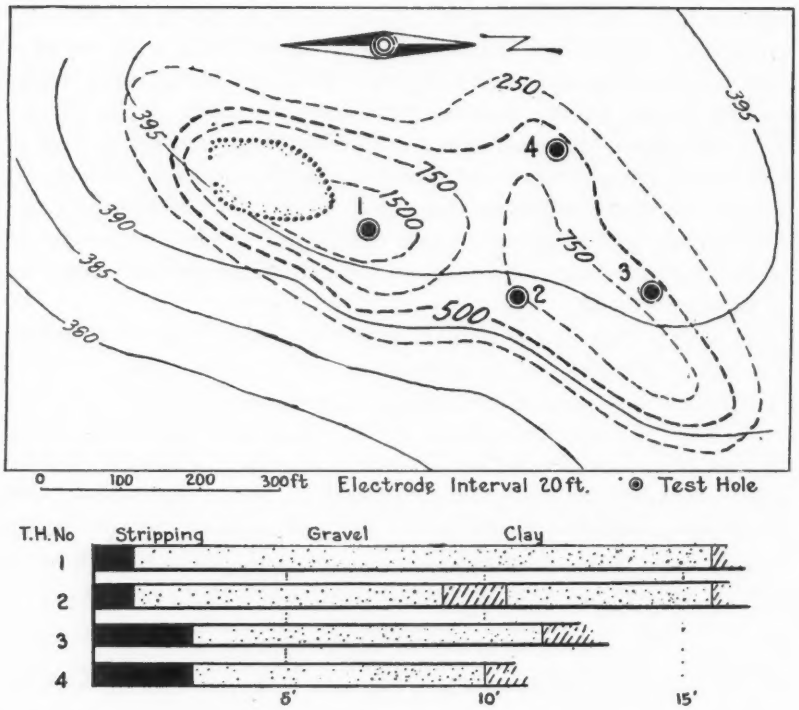


FIG. 4. Rock County Prospect. Electrode interval is 20 feet. See Fig. 1 for notation.

streams moving large volumes of sand and gravel which were deposited as valley trains. After the recession of the water, these deposits were slowly eroded away to be replaced by silt and clays. Today only remnant islands of gravel remain in the topographically lower parts of these valleys, for the most part buried beyond recognition by surface indications.

Such was the probable history of the Luverne prospect located in Southwestern Minnesota, thirty miles below the rugged terminal moraine hills of the "Coteau des Prairies."

Four random test holes (1A, 2A, 3A, 4A) had been dug on the west end of the pit (See Fig. 5) before the geophysical survey was undertaken. Test hole No. 2-A was spotted on the edge of a gravel island and gives misleading data. A ten foot electrode interval was used to outline the edge of the deposit remaining on the south side of the pit.

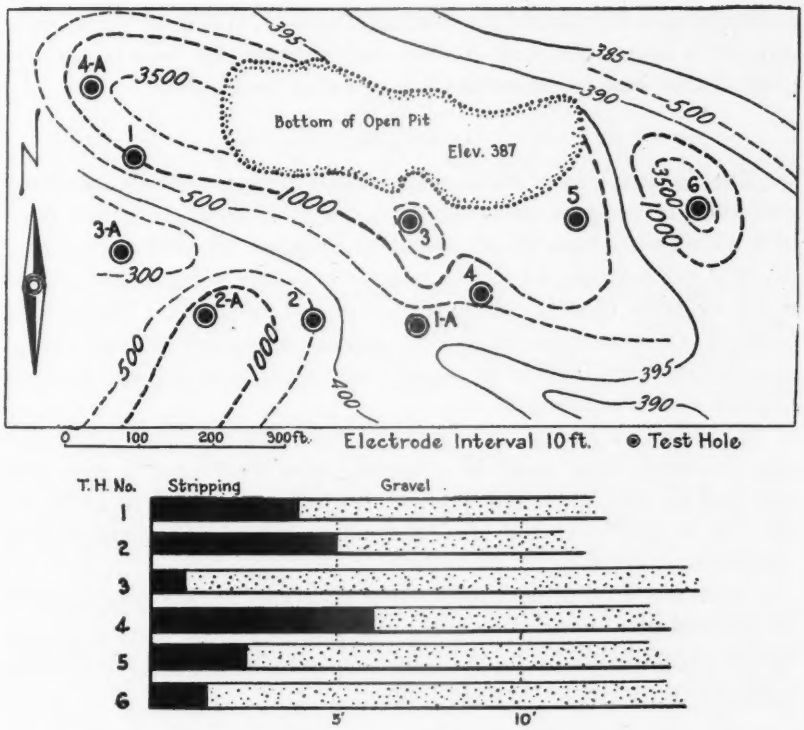


FIG. 5. Luverne Prospect. Electrode interval is 10 feet. See Figure 1 for notation. Following approximate correlation of resistivity to depth of stripping was made:

Resistivity, ohm-feet	*Depth, feet*
3500	1.5
2000	2.5
1000	4.0
500	5.0 or more

This small electrode interval was chosen so that the earth section could be considered to be a two layer one—stripping and gravel—and thus eliminate any effect from the base of the deposit. The correlation between apparent resistivity and stripping thickness is good since the test holes check the predicated thickness reasonably well. From the plan map it is easy to estimate the stripping and gravel quantities, using the thickness of the gravel section determined from test holes.

When a test hole placed on an earth-resistivity contour failed to check the assumed overburden relationship, the inference is that clay lenses exist in the deposit or else the deposit is thin. Numerous field

examples have been found illustrating this point. When the stripping is uniform a longer electrode interval will contour the base of the deposit, if that base is the water table or a clay horizon.

CONCLUSION

The classification of the earth materials of the subsoil by electrical resistivity traverses is essentially the same problem as studying a bore hole with electro-logs. Much useful information for civil engineering projects can be obtained in this manner and large sums of money and much valuable time saved. Sand and gravel prospecting is only one example. Others would be rock classification, studies preliminary to excavation, investigations of swamps and peat bogs, and the location of preglacial river channels.

If a resistivity traverse were combined with a self-potential survey, pertinent data could be obtained when used along a proposed pipe line right-of-way. Not only could the kind of material to be excavated be predicted, but also information regarding soil electrolysis would be available.

After the war, undoubtedly large civil engineering projects will be planned on a world-wide scale, and greater recognition than heretofore will probably be given to the time and labor-saving possibilities of shallow geophysical investigations.

MAGNETIC INTERPRETATION*

DART WANTLAND†

ABSTRACT

It is common knowledge that magnetic anomalies do not always correspond to structural uplifts. The author discusses this problem under the headings of: (1) Examples, (2) The magnetic character of sediments, (3) Possibilities of magnetic stratigraphic studies, (4) The place of magnetic surveying.

INTRODUCTION

This paper grew out of a discussion between the writer and Ronald K. De Ford, geologist of Midland, Texas, concerning the observation that there is sometimes, but not generally, a direct correspondence between known geologic structure and observations of the vertical intensity of the earth's magnetic field.

There is a tendency to lose sight of the fact that a magnetic survey is the result of surface observations of variations from normal of the earth's magnetic field, and that these variations are due to variations laterally of the magnetization of rock units, as well as to variations in their thickness and depth.

Examples will be shown of situations in which there is: 1.) a direct correspondence between structural uplift and magnetic intensity (Amarillo Ridge); 2.) an inverse correspondence between structural uplift and magnetic intensity (Garber Field); 3.) axial shift between structural and magnetic highs, which may be due either to the inclination of the earth's field (Hobbs Field) or to the effect of a shallow magnetic formation (Brousseau). There are undoubtedly hundreds of examples of these situations in the files of oil companies which have made extensive magnetic surveys.

A brief discussion will be given of the question of the magnetic character of sediments and of the possible influence of sedimentary structure on magnetic results and of the desirability of magnetic stratigraphic studies as an aid to the geologic interpretation of magnetic surveys.

EXAMPLES

The magnetic and subsurface observations of a portion of Carson County, in the Panhandle of Texas, appear to offer an example of a situation in which there is a direct relationship between subsurface

* Presented at the Denver meeting, April, 1942.

† Department of Geophysics, Colorado School of Mines, Golden, Colorado.

structure and the magnetic map. Fig. 1 shows a magnetic survey of this area,[1] contoured at an interval of 50 gammas, on which the locations, surface elevations, and elevations of the lime and granite wash for four wells are given. Fig. 2 shows a magnetic and geologic profile at

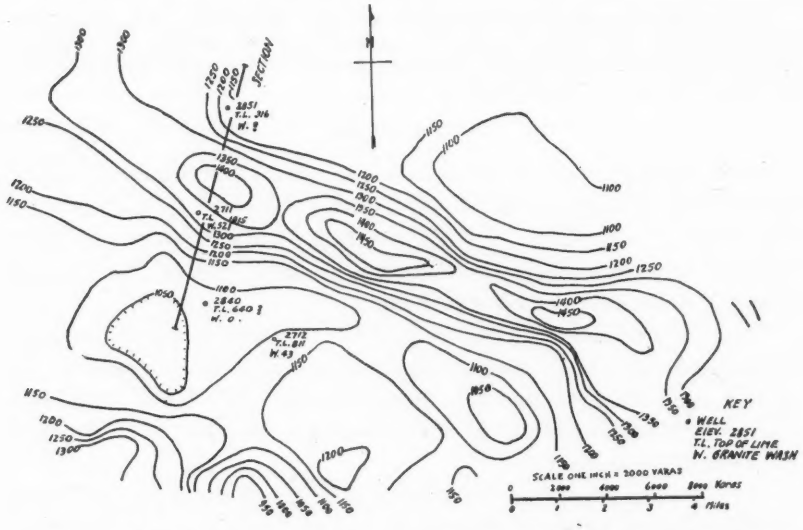


FIG. 1. Magnetic map over a portion of the Amarillo Ridge in Carson County of the panhandle of Texas, after Heiland. Contour interval 50 gammas. Locations and surface elevations of four wells shown, and depths of top of lime and of granite wash. (See Fig. 2 for cross-section.)

right angles to the strike of the axis of the magnetic anomaly in the vicinity of the wells.

Igneous rocks are generally assigned much higher values of magnetic susceptibility[2] than the Permian red beds, evaporites, and limes that make up the sedimentary section in this area, so that it is reasonable to assume that the magnetic anomaly shown on the map and cross-section is due to the structural uplift of the granites of the Amarillo Ridge. It is of some interest, also, to see if the shape and breadth of the magnetic anomaly are consistent with the assumption that it is the result of the structural uplift of the granite.

Various rules for the depth of the equivalent magnetic pole[3] which can result in a magnetic anomaly can be set up, each dependent on an

[1] From Heiland, C. A., *Geophysical methods of prospecting*, Colorado School of Mines Quarterly, Vol. 24, No. 1, p. 64, (March, 1929).

[2] Heiland, C. A., *Geophysical Exploration*, pp. 312–314. Prentice-Hall, New York. 1940.

assumption regarding the shape of the magnetized body; or the excellent curves of Nettleton[4] can be utilized to approximate the shape and depth of a body which will give the observed magnetic anomaly.

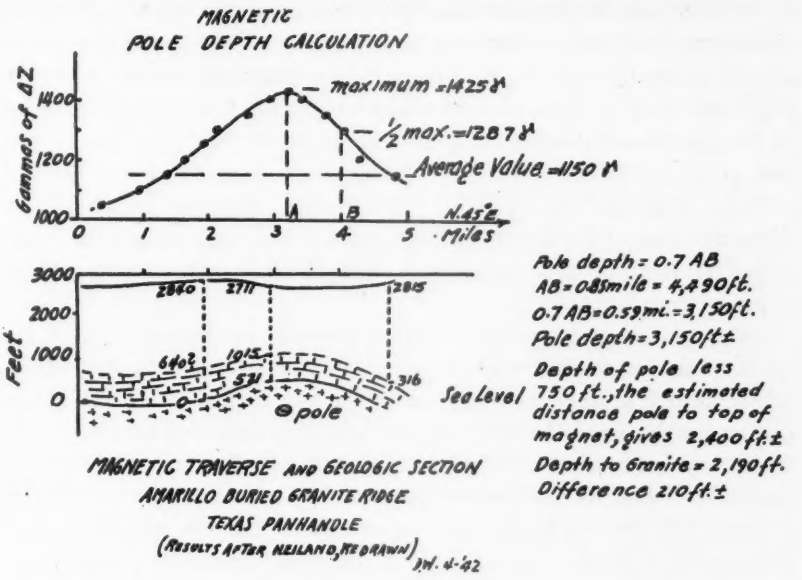


FIG. 2. Example of magnetic pole depth calculation for the magnetic profile along the line of section shown on Fig. 1.

It is sufficient for the case at hand to assume that the magnetic effect of the high point on the ridge through which our cross-section passes can be represented as the result of a single pole, for which the depth rule is that the depth of the pole is 0.7 the half-width of the anomaly at its half-maximum value.

Determination of the half-maximum value requires knowledge of the base value of magnetic intensity in the area, where it is unaffected by the magnetic anomaly. In the example of depth computation being presented the base value was taken as 1150 gammas, as shown in the profile of Fig. 2 and as represented by the 1150 gamma contour of Fig. 1. Then the half-maximum value is 1287 gammas, and the half-width of the anomaly at its half-maximum value 0.85 miles or 4,490 feet. Consequently, according to the depth rule, the pole depth is 0.7

[3] See Heiland, C. A., A.I.M.E. Transactions, *Geophysical Prospecting*, 1932, p. 212, for a discussion of various depth rules.

[4] Nettleton, L. L., *Gravity and magnetic calculations*. GEOPHYSICS, Vol. VII, No. 3, p. 293, (July, 1942).

of this distance, or 3,150 feet. The observed depth of the granite at its highest point is 2,190 feet, i.e., the computed pole depth is 960 feet below the top of the granite.

It is general experience that the location of the "pole" is within the magnetized body a distance depending on the shape of the body, among other factors. N. H. Stearn,[5] in a magnetic survey across a peridotite plug in Arkansas of about the same depth as the granite in the case under discussion found the depth of the "pole" to be 750 feet greater than the depth to the top of the plug as determined by drilling. If we use this figure of 750 feet as a correction factor on our determination of the depth to the granite in this case we get the computed depth to be 2400 feet, which differs by 210 feet from the actual depth of 2190 feet.

The apparent precision of this result should not be taken seriously, since the assumption of a single pole is not consistent with the mainly linear nature of the anomaly, and since the depth determination is quite sensitive as to the base value of intensity assumed—for example, if this had been taken as 1100 gammas, the pole would have been calculated to have been deeper by 550 feet. Nevertheless, the calculation is good enough to justify the expectation that the magnetic high mapped in this area results from a magnetic source at a depth approximately that of the surface of the granite, and that the magnetic high can be correlated with the granite high.

An example has been shown of direct association between a structural uplift and of a positive magnetic anomaly. The next example will be of a case in which the relation between the uplift and the anomaly is inverse to this.

Fig. 3 shows a magnetic profile[6] and a geologic section[7] across the Garber Field of Garfield County, Oklahoma. This is one of the numerous fields on local uplifts along the Nemaha granite ridge which extends from Oklahoma City, across Kansas, into southeastern Nebraska. The magnetic low may be due to the cutting out by erosion of a highly magnetic sedimentary formation, the thickening of such a bed off-structure, or increase in the content of magnetic material off-structure. It may equally well be due to lateral variations in the susceptibility of the basement rocks, with the core of the ridge occupied by

[5] Stearn, N. H., *Geomagnetic exploration with the Hotchkiss Superdip.* A.I.M.E. *Geophysical Prospecting*, 1932, p. 197.

[6] After an early survey by L. Spararagen, *Oil and Gas Journal*, Vol. 27, No. 26, p. 42 (November 15, 1928).

[7] From *Oklahoma Geological Survey Bulletin* No. 40H.

lighter, more mobile, more acidic and thus less magnetic rocks, than those which are at the flanks of the structure. Which of these explanations is correct could only be established by determination of the magnetic susceptibility of the formations, including the basement rocks, which are present on and off structure.

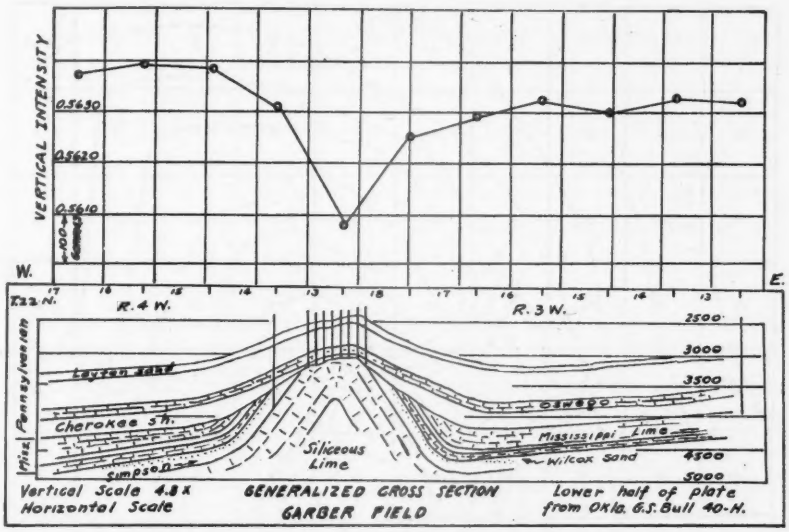


FIG. 3. Magnetic profile (after L. Spararagen) and generalized geologic cross section (after Oklahoma G. S. Bulletin 40-H) of the Garber oil field of Garfield County, Oklahoma.

In many cases there is neither exactly direct nor exactly inverse correspondence between magnetic highs and structural highs, but the magnetic axis (if it exists) may be shifted a greater or lesser amount from the structural axis. The Hobbs Field of Lea County, New Mexico is an example. Fig. 4, from Jakosky,[8] shows the subsurface contours on the white lime, (solid lines), and the magnetic contours (dotted lines). It will be noted that the magnetic high is located some 1.7 miles southeast of the highest structural point on the white lime, a Permian marker at a depth of about 4000 feet.

In the northern hemisphere, a southward shift of the magnetic from the structural axis is to be expected, due to the northward inclination of the magnetic field of the earth. The nature of this shift is

[8] Jakosky, J. J. *Exploration Geophysics*, p. 142. Times-Mirror Press. Los Angeles, 1940.

illustrated in Fig. 5 for the idealized case of a sphere magnetized by induction. It should be noted that the magnitude of the shift is a function of the diameter, but not of the depth of the sphere.

Suppose that we assume that the actual magnetic material producing the magnetic anomaly at Hobbs can be replaced by a sphere

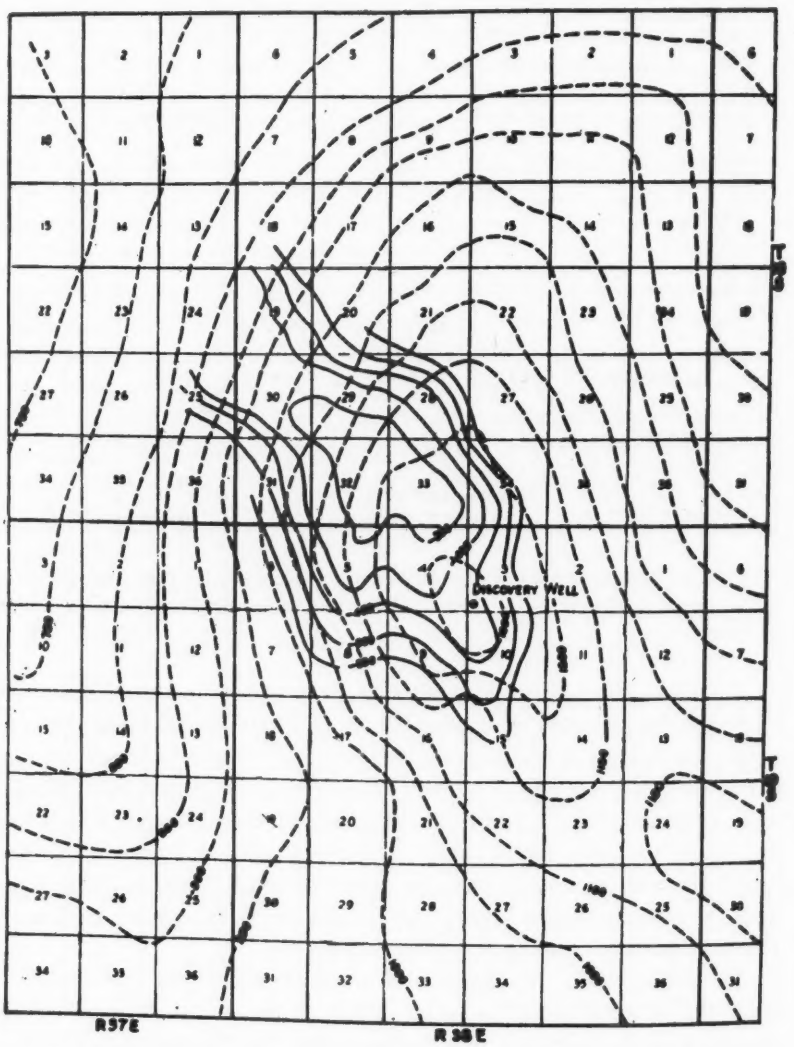


FIG. 4. Magnetic contours of vertical intensity (dotted) and structural contours at the top of the White Lime (solid), Hobbs Field, Lea County, New Mexico (from Jakosky). Magnetic contour interval is 50 gammas, structural contour interval is 50 feet.

with a diameter of five miles, which is about as large as can be tolerated in view of the breadth and shape of the anomaly. Since the inclination of the earth's magnetic field at this latitude is 61°, the theoretical shift of axis for a 5 mile sphere would be 1.2 miles, which would explain the major part of the 1.7 mile shift observed. On the other hand, no deep drilling has been done at Hobbs to date, so there is no *a priori* reason for expecting that the axis of the structure at greater depths, particularly at the depth of the basement complex, will conform to that on the white lime.

Another example of shift of magnetic from structural axes is to be found in the Duvernay-Brosseau area some 70 miles east of Edmonton, Alberta, Canada.[9] Fig. 6, redrawn from Heiland, shows the surface geological structure contours on the Lea Park-Ribstone Creek contact (light dashed line), the core drill contours on the base of the upper Lea Park sandstone, (light solid line), the seismic reflection contours at a depth of about 1000 feet, (heavy solid line) and the magnetic contours (dotted line). The contour interval for the surface work is 10 feet, for the core drill work 10 feet, for the seismic work 25 feet and for the magnetic work 500 gammas. Fig. 6 also shows the upper part of the geologic cross-section of the area through three deep tests.

It will be noted that the surface structure shows an axis with a northwest-southeast trend, that the core drill map is showing purely local structure on the upper Lea Park, and that the magnetic map is an expression of the topography and/or thickness of the presumably highly magnetic Ribstone Creek sandstone. None of these surveys correctly represent the deep structure which is expressed by the seismic results, which were checked by drilling.

Measurements of the susceptibility of cores cut from the Ribstone Creek sandstone, which was pierced by many core holes in this area, would definitely have confirmed whether or not this formation is the source of the magnetic anomaly.

THE MAGNETIC CHARACTER OF SEDIMENTS

Certain lines of evidence tend to show that the majority of magnetic features are associated with and arise from basement rock. Dr. L. L. Nettleton[10] presents very cogent facts along this line. Such an

[9] Heiland, C. A. *Geologic, magnetic, reflection work and drilling at the Duvernay-Brosseau structure,* Alberta, Canada. Colorado School of Mines, *Geophysical Studies,* 1932–36, Vol. 32, No. 1, p. 13 (January, 1937).

[10] Nettleton, L. L. *Geophysical Prospecting For Oil,* McGraw-Hill, New York, pp. 199–205, 1940.

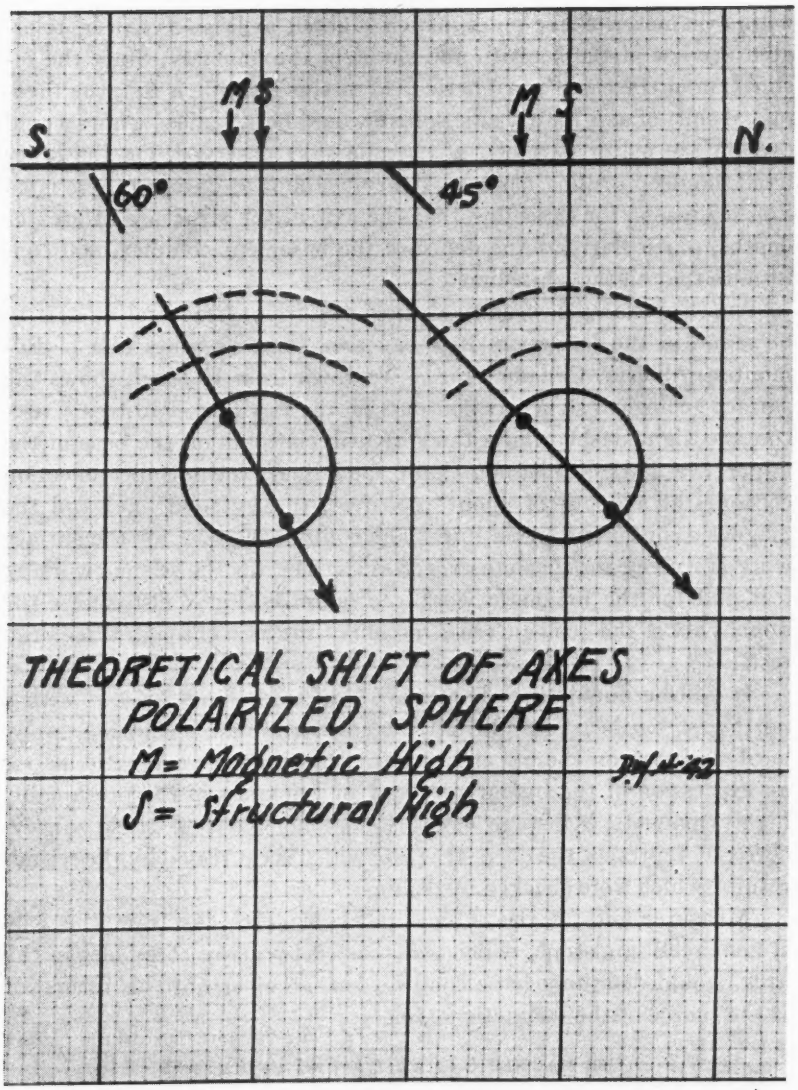


FIG. 5. Illustrating theoretical shift of axes, assuming a uniformly magnetized sphere. (Note: 45° of north magnetic dip occurs in the vicinity of 19° N. latitude, or somewhat south of Mexico City. 61° of north magnetic dip occurs at Hobbs, New Mexico, at about 33° N.)

idea, that magnetic surveys showed the configuration and character of magnetic basement rock, was the main basis of the interpretation of earlier magnetic surveys.

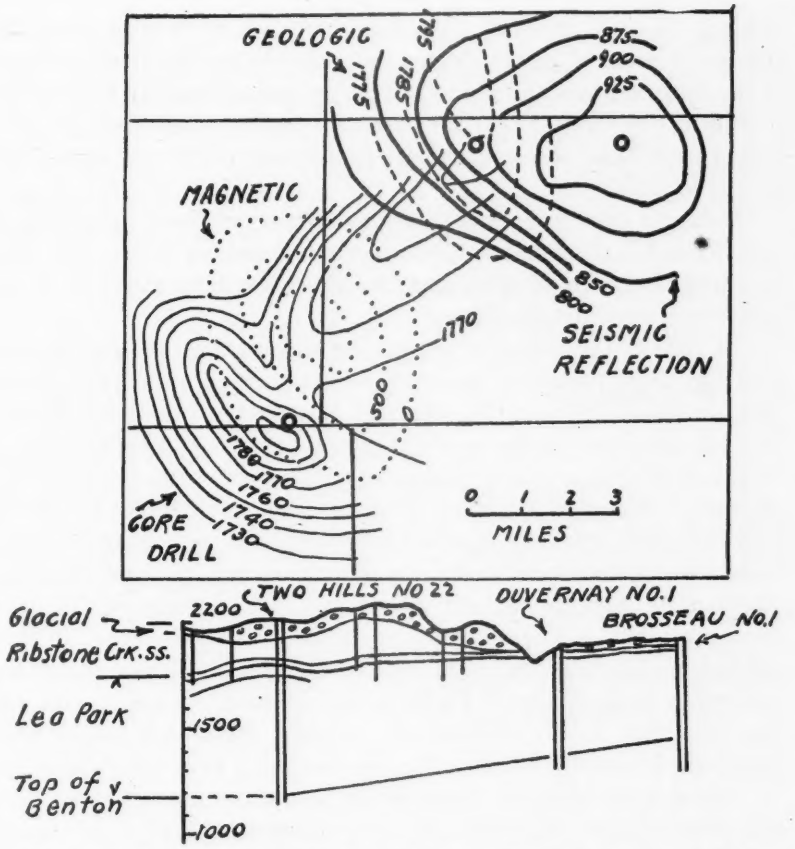


FIG. 6. Geologic and geophysical results at the Duvernay-Brosseau structure, Alberta, Canada (after Heiland). Surface geologic contours on contact of Lea Park-Ribstone Creek are dashed lines at 10 foot contour interval. Dotted lines are magnetic contours at interval of 500 gammas. Light solid lines are contours on the base of the upper Lea Park sandstone of Upper Cretaceous age from core drilling. Contour interval is ten feet. Heavy solid lines are seismic contours on the first reflecting horizon. Contour interval is 25 feet.

On the other hand, there is also evidence to support the idea that in some areas the configuration and magnetic character of a high susceptibility portion of the geologic section above the basement is the feature mapped by the magnetometer. The work of W. P. Jenny[11] and of Wm. M. Barret[12] are in point in this connection. This is par-

[11] Jenny, W. P. *The magnetic method and its interpretation problems,* International Oil, Vol. 1, No. 2, pp. 53–57. July 1940.

[12] Barret W. M. *Mapping geologic structure with the magnetometric methods.* W. M. Barret, Inc. Shreveport, La. 23 pgs. February 1937.

ticularly so since much of their published data deals with magnetic surveys in areas of gently sloping sediments in the southern portions of the state of Texas and in the Mississippi embayment. In these areas it is logical to suppose that the basement rock is at great depth, perhaps 15,000 to 20,000 feet, and for that reason effectively out of the magnetic picture.

However, no measurements of susceptibility of the sediments have been offered in absolute units, which could be used as the basis of computation of the size of the anomalies which would be expected to result from known structural relief.

In view of the difference of opinion which exists, the earlier idea that the major portion of magnetic effects mapped always arise from and are associated with the basement may well be examined further. It is felt that such an idea would require that in general high magnetic values should occur where basement rock comes to the surface. This appears, however, not always to be true. In the vicinity of Golden, Colorado, the pre-Cambrian meta-sedimentaries of the front range, which are the basement rocks, are quite non-magnetic and magnetic readings on them are not particularly high. This outcrop of basement rock, if a range of mountains may be so designated, is in fact, in that portion of Colorado cited, somewhat low magnetically as was demonstrated by G. B. Somers.[13] He found by a magnetic traverse from the pre-Cambrian to the sedimentary covered areas that pronounced magnetic features were not encountered until over the sediments.

There is no intention to imply by the above that the magnetic character of basement rock and changes therein are not important in magnetic work. In fact, situations may arise in which differences in magnetic character in the basement would show up in a magnetic survey that have no geological structural significance and are related only to the mineralogical and petrographic character of the basement complex.*

It would also follow logically, that where basement rock is highly magnetic mountain ranges composed of such rock would show high magnetic values. From considerations based on Fig. 3 and substanti-

[13] Somers, G. B. *Anomalies of vertical intensity*, (D.Sc. Thesis), Colorado School of Mines Magazine, Issues of August through December, 1930, and February, 1931. Denver, Colorado.

* For an analogous situation which might arise in gravimetric surveying, see Fig. 6 of Romberg and Barnes' paper, *Correlation of gravity observations with the geology of the Smoothingiron granite mass, Llano County, Texas*, in this issue of GEOPHYSICS. (Editor's Note.)

ated by Fig. 6, it is considered that in addition to magnetic basement rock effects there are also significant effects from magnetic sedimentaries to be dealt with in magnetic interpretation. These latter features when mapped magnetically and recognized, may in some cases give useful geologic information in themselves. The examples presented bring out the variability of the degree of agreement between magnetic results and geologic structure exhibited in different situations.

POSSIBILITIES OF MAGNETIC STRATIGRAPHIC STUDIES

In an effort to distinguish between magnetic effects arising from basement situations and from magnetic sedimentary beds it is felt that magnetic examination and susceptibility determinations of well samples and cores might shed light on the problem. Such studies can answer the question as to the presence of markedly magnetic horizons, and their thickness, to depths reached by the samples available.

Along the same line broad scale studies of magnetic character and susceptibility determinations of basement rock outcrops would furnish a factual background for interpretation of anomalies in areas not too distant from such outcrop localities. This would be a form of what might be called magnetic stratigraphic investigation. For example, anomalies in geologic basins where basement rock was known to be highly magnetic as quantitatively determined could logically be considered to arise from basement configuration to a large extent. In like manner sedimentary causes would be more reasonable where basement rock was found to be relatively non-magnetic as in the case previously cited for the local Colorado Front Range.

Another phase of the matter would be the probability of sedimentary magnetic effects based on the thickening or thinning of the geologic section or portions thereof where source rocks making up the sediments were known to be in themselves magnetic. Such investigations would be analogous to the seismic average velocity determinations, achieved by well shooting, which are utilized in the seismic reflection method.

THE PLACE OF MAGNETIC SURVEYING

In the cases cited and the various features treated it has been shown that by their nature magnetic survey results do not lend themselves, in many instances, to direct correlations of high accuracy between anomalies mapped and underlying geologic structure. The magnetometer, however, can perform efficiently and at low cost certain

functions in petroleum exploration. Suitable areas for magnetic exploration have been set up and neatly described in the recent A.A.P.G. Symposium volume of 1941, entitled *Possible Future Oil Provinces of the United States.*

It is felt that the magnetic method can most advantageously be used as a first method in reconnaissance of a number of these provinces or large portions of them. This opinion is based, in part, on the results of such a survey in one of these provinces with which the writer was associated. In this case some 3,500 magnetometer stations gave very pertinent information as to the grain of the subsurface, the probable strike and character of several large tectonic features and the extension of known structure into geologically hitherto unknown areas. While no locations for deep tests could be attempted from such work alone, a number of localized areas were set up that, from the data obtained, were well worthy of detailed study by geophysical methods of higher resolving power. Other areas were designated as of probably little or no importance. It is not considered that the particular province noted was more favorable for magnetic work than a number of others described in the volume referred to.

It is also worthy of consideration that as more data are obtained on magnetic results and their significance geophysicists will be better able to cope with the problems of exploration in those vast unexplored areas of the other continents of the world when international relations again permit peaceful arts to be pursued. In such future development it is felt that the magnetic method will play a useful part in evaluating large regions and localizing portions of them which are suitable for more detailed investigation.

DISCUSSION

In the field of petroleum exploration, progress in the technique of interpretation of magnetic surveys appears to be following to a great extent the recognition and application of the fact that variations in the magnetic susceptibility of sedimentary formations may cause mappable variations in the magnetic intensity of the earth's field.

In 1929, the writer investigated the magnetic susceptibility of shallow core hole samples of shales and unconsolidated sandstones in the Gulf of Mexico embayment area of South Texas.* Average magnetic susceptibilities of a number of sand cores were found to have approximately twice the value of the average of a number of shale cores taken from an interbedded formation. Individual samples showed a wider variation than this between shales and sands. At the same time a correlation was noted between magnetic susceptibility and content of magnetite or other magnetic mineral grains in the sample.

* *Magnetic susceptibility and magnetic content of sands and shales.* Bulletin of American Association of Petroleum Geologists, Vol. XIV, p. 1187.

As pointed out by Wantland, the conditions of origin and source rocks may influence the magnetic mineral content of considerable thicknesses of sedimentary formations. The thinning, thickening, configuration and attitude of such formations contrasting in magnetic susceptibility cause magnetic anomalies in the earth's field from which the structural features present may be interpreted.

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The second paragraph of the introduction to Mr. Wantland's paper, if amplified by a second one, would give the key to a real understanding of the problems of magnetic interpretation. This second statement should be that any interpretation of magnetic data should fit the observed distribution of magnetic intensity quantitatively as well as qualitatively. It is not until we ask quantitative questions that much progress can be made.

For instance, consider the case of the Hobbs magnetic anomaly discussed by Mr. Wantland in his paper. The magnitude of this anomaly is about 500 gammas. If this anomaly were due to basement uplift, the uplift would amount to several thousand feet and igneous rocks would be at shallow depths on top of the structure. It is apparent, therefore, from quantitative considerations that the anomaly is mainly due to a change in the character of the basement rocks. Since the great mass of the rocks causing the anomaly lies below the basement surface, there is no reason why an associated uplift should coincide with the center of the anomaly even assuming vertical polarization. Under such circumstances, we should look for a secondary anomaly which might be quantitatively associated with the structural uplift of the basement. At Hobbs such a secondary anomaly exists and it coincides reasonably well with the known structure as mapped on the sedimentary beds.

Garber is cited as an example of a structure associated with a sharp magnetic low. Unfortunately, we have never seen a magnetic map of Garber made before drilling. However, the present sharp low at Garber can be accounted for quantitatively by the casing in the wells. This is another example where the quantitative approach to the interpretation of magnetic data materially modifies the conclusion.

The question of magnetically active sediments and their role in the interpretation of magnetic surveys has been the subject of much thought and investigation. We all can cite examples of magnetically active sedimentary rocks. However, over vast areas there is little evidence to lead one to believe that the sediments are sufficiently magnetically active that their contribution to the magnetic picture can be used to infer sedimentary structure. We have made magnetic measurements on well cuttings of the Permian and Pennsylvanian in Oklahoma and of the Permian of West Texas. The values of polarization and susceptibility were uniformly very low, and, as a matter of fact, small pieces of steel abraded from the drilling bit were the major source of the magnetic properties that were found. We believe, however, that magnetic measurements on sedimentary rocks should be made so that their contribution to the magnetic picture can be evaluated. In view of our experience, well cuttings are not very satisfactory for this purpose.

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ASSOCIATION OF MAGNETIC AND DENSITY CONTRASTS WITH IGNEOUS ROCK CLASSIFICATIONS*

L. L. NETTLETON AND T. A. ELKINS†

ABSTRACT

The frequent co-existence of strong magnetic and gravity anomalies directs attention to the properties of igneous rocks which may account for them. Density data are direct and unambiguous but magnetic data are much less certain. On the assumption that it is determined by disseminated magnetite, the susceptibility can be estimated from the proportion of magnetite in the rock. The possibility of estimating magnetite content from chemical analyses is examined and while not very satisfactory, it probably gives relative values of some merit. From published chemical analyses the magnetite content and probable intensity of magnetization are calculated for some 1450 samples of igneous rocks, for which density values are also given. The values and resulting contrasts are analyzed statistically and tabulated for the C.I.P.W. and the Iddings methods of classification. The contrasts, thus determined, are in reasonable agreement with expectations from the analysis of magnetometer and gravimeter surveys.

INTRODUCTION

The extensive gravimeter surveys of the past few years together with the wide areas covered with the magnetometer have resulted in many areas which are fairly closely and regularly covered by both instruments. For both types of survey it has long been recognized that the larger and more conspicuous features must have their origin in the igneous basement below the sedimentary rocks. In many instances the large gravity and magnetic features are similar in form and roughly co-extensive in area. Therefore, it is of interest to consider the sources and probable values of the magnetization and density of igneous rocks in order to anticipate, if possible, the order of magnitude of the magnetic and density contrasts which might be expected. Such values should be an aid in the analysis of individual cases of corresponding gravity and magnetic anomalies to determine whether or not their magnitudes are reasonable expressions of different geophysical aspects of the same body of igneous rock.

A fair body of data on densities of samples of igneous rocks is available and such information is quite direct and straightforward so that the averaging of measurements of a large number of samples should give reasonable values for densities of typical igneous rocks. Corresponding magnetic values are much less direct for several reasons:

* Read at Annual Meeting of Society of Exploration Geophysicists, Fort Worth, Texas, April 7, 1943.

† Gulf Research & Development Company, Pittsburgh, Pa.

(1) The fundamental source of magnetism is not as simple as is that of density. (2) Measured values of magnetic susceptibility are dependent on the intensity of the field in which the measurements are made and many of the published values were determined in fields much higher than that of the earth. (3) The range of individual sample values is very wide so that the choice of a reasonable average is much more difficult than for density. For these reasons the material which follows is much more concerned with probable magnetization contrasts between different classes of igneous rocks than with the corresponding density contrasts.

FUNDAMENTAL THEORETICAL CONSIDERATIONS

It is well known that magnetite is by far the most common and the most magnetic of the minerals which may contribute to the magnetic properties of igneous rocks. Therefore, it seems reasonable to neglect the possible magnetic contributions of the other relatively rare and much less magnetic iron minerals such as ilmenite, franklinite, vivianite, hematite, etc., and to assume that the susceptibilities of typical igneous rocks are directly related to their content of magnetite.

Consider that a magnetizable rock is composed of individual particles of magnetite disseminated through a non-magnetic matrix so that the particles are separated by distances of several times their diameter. To the extent that the individual particle can be approximated by an ellipsoid, the magnetization I_i of a single such particle will be determined by the applied field H_e, by the susceptibility of the material, k_0, and also, to a very great degree, by the demagnetization factor, λ, as shown[1] by the relation

$$I_i = \frac{k_0 H_e}{1 + k_0 \lambda}.$$

If a rock has a volume fraction, P, of magnetite, the magnetization of the rock as a whole will be[2]

$$I = PI_i.$$

[1] For a mathematical derivation, see, for instance, A. G. Webster, *Electricity and Magnetism* (McMillan, 1897), pp. 370, 371.

[2] This ignores the demagnetization effect for the rock as a whole, but in this case, where the effective susceptibility is low, this is not a very important factor, as is indicated by Table I.

Then the effective susceptibility, k, of the rock as a whole will be

$$\begin{aligned} k &= I/H_e \\ &= PI_i/H_e \\ &= \frac{Pk_0}{1 + k_0\lambda} \\ &= Pk', \quad \text{where} \quad k' = \frac{k_0}{1 + k_0\lambda}. \end{aligned}$$

It is evident that if we knew the volume percentage of magnetite in a rock together with some way to evaluate k', we could calculate the effective susceptibility.

Grenet[3] apparently was the first to consider carefully the geometric and demagnetization factors and to point out that, for disseminated magnetite in rocks, the effective susceptibility (k') is only slightly dependent on the susceptibility of the magnetite itself (i.e., on k_0). Grenet gives a table of this relation for spherical particles which (slightly extended) is given here as Table I.

TABLE I

Relation between mineral susceptibility (k_0) and effective susceptibility of rock (k') for disseminated spherical particles

k_0	k'
0.01	.0096
0.1	.0705
1	.193
5	.228
10	.233
100	.238
∞	.239

If the particles are not spherical in form but are elongated, the value of k' will be larger than the above figures if the magnetization is in the direction of the long axis and less if in the direction of the short axis. For instance, Grenet calculates that for an ellipsoid of revolution with a ratio of long to short axes of 10, the value of k' is 2.08 (for $k_0 = 10$) for magnetization along the long axis, and .156 for magnetization along the short axis. For the same ellipsoid, the mean value of k' for the three axes is .797.

On the basis of the above figures, Grenet calculates that as a

[3] G. Grenet: *Sur les Propriétés Magnétiques des Roches*, Annales de Physique, Tenth Series, Vol. 13, March 1930, pp. 263–348.

rough average the effective susceptibility of magnetite disseminated in small particles (i.e., the value of k') should be about 0.25.

EXPERIMENTAL TESTS OF THE EFFECT OF MAGNETITE ON ROCK SUSCEPTIBILITIES

The foregoing considerations have indicated that we should expect to be able to calculate the susceptibility of a rock containing a volume proportion, P, of disseminated magnetite as

$$k = Pk'$$

with k' having a value in the neighborhood of 0.25. Conversely, if we have examples of measured values of susceptibilities of rocks for which the magnetite content has been measured or estimated, we can calculate k' from these values for comparison with the value expected.

Slichter,[4] in the early days of magnetic prospecting, made fundamental studies of the properties of magnetite including a study of the effective susceptibility of powdered magnetite when disseminated through a non-magnetic matrix. Slichter's Fig. 6 (reproduced here as Fig. 1) is, in effect, a measurement of the value of k' for various proportions of magnetite. The value decreases regularly to about 0.27 for very small magnetite concentrations. Almost as low a value is shown when the magnetic material is powdered iron, for which the susceptibility for the material (*i.e.*, k_0) must be much larger than for magnetite. These curves are just what would be expected from the theoretical conditions outlined above, as the conditions postulated in calculating Table I should be approached at the right side of Fig. 1. The fact that at low concentrations the value of k' for iron is almost as low as that for magnetite is explained by the small effect of the value of k_0 on k' when k_0 is larger than about one. (See Table I.) The slightly higher value of k' than that calculated for spherical particles may be explained either by the particles' being somewhat elongated with a small degree of alignment parallel to the field or by the aggregation of individual particles into groups elongated parallel to the field, or both. We can consider that Slichter's work on powdered magnetite has given an experimental value of k' of about 0.27. Thus the theory pointed out by Grenet has given a good explanation of Slichter's experiments, although Slichter did not consider the demagnetization

[4] L. B. Slichter: *Certain Aspects of Magnetic Surveying.* Geophysical Prospecting 1929. Trans. Am. Inst. Min. Met. Eng., Vol. 81, pp. 238–258.

effect and Grenet apparently did not know of Slichter's work.[5]

Slichter's paper (page 242) includes measurements of susceptibility on two samples of gabbro, for which the magnetite content was determined by pulverizing the rock and separating with a magnetic separator. From the data there given we can calculate experimental values of k' as follows:

Sample	*Measured Susceptibility* (k)	*Magnetite Content by Volume* (P)	*Calculated* k'
1	.00043	.0015	.29
2	.00068	.0024	.28

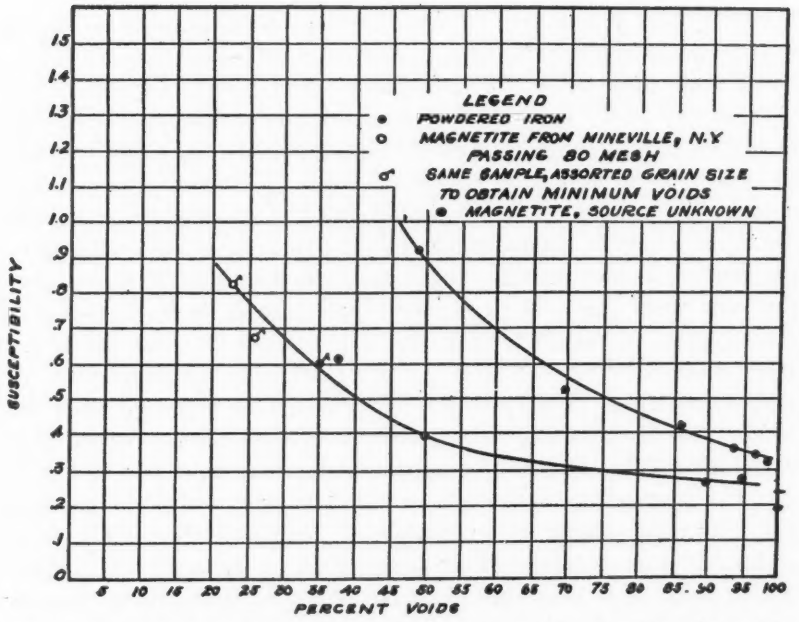

FIG. 1. Specific susceptibility of powdered magnetite and powdered iron in various concentrations in a non-magnetic matrix. (After Slichter)

These data are included among those assembled in Fig. 2.

Collingwood[6] made measurements of magnetite content and susceptibility of sands and shales and his Table I (p. 1189) contains twelve sets of data from which values of k' can be computed. These

[5] Grenet's paper contains a bibliography of 64 titles but does not include Slichter's paper, which is dated nearly two years earlier.

[6] D. M. Collingwood: *Magnetic Susceptibility and Magnetite Content of Sands and Shales.* Bull. A.A.P.G., Vol. 14, No. 9 (Sept. 1930), pp. 1187–1190.

values are very erratic, ranging from 0.18 to over 10, and nearly all are much too high to be reasonable. It seems probable that the magnetite separation—"the magnetite grains were removed with a magnet"—was incomplete and that a relatively large proportion of very finely divided magnetite may have been lost. Also, the susceptibility was measured in a relatively high field ("18 gauss"). Both these causes would tend to give k' values which are too high. For these reasons, these k' values have not been considered further.

Grenet measured the susceptibilities of a large number of samples of the principal igneous rock types. He also estimated the percentage

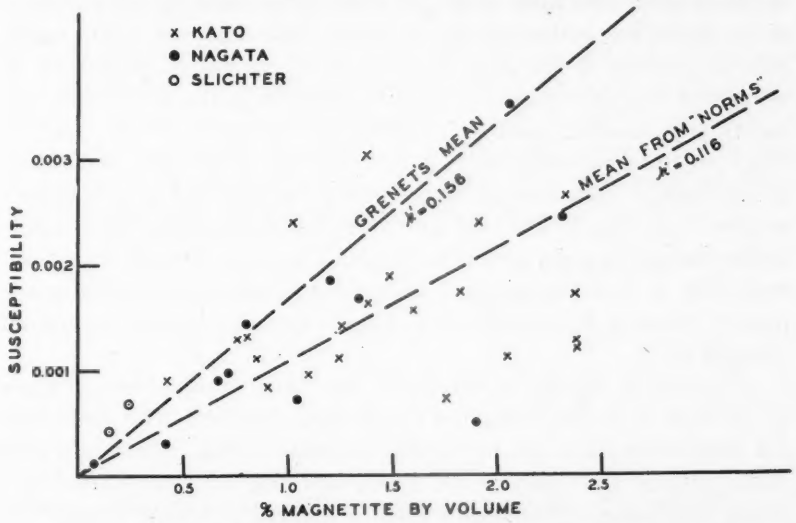

FIG. 2. Measured susceptibilities of rocks with various magnetite content. Points by Kato and Nagata are from individual samples, with magnetite determined by "norms" from chemical analysis. Points by Slichter are from individual samples, with magnetite determined by a magnetic separator. "Grenet's Mean" is average ratio of susceptibility from 86 samples, with magnetite determined by thin sections. "Mean from Norms" is average ratio of susceptibility to magnetite for all the Japanese samples.

of magnetite by measuring the ratio of the area of dark minerals to total area of a thin section of the same rock under the microscope on the assumption that all of the dark minerals were magnetite.[7] Grenet's

[7] It can be shown that for a homogeneous texture containing disseminated particles, the ratio of the area of such particles cut by an arbitrary plane to the total area cut is the same as the ratio of the volume occupied by the particles to the total volume, provided the area of the surface is large enough in comparison with the particle size to give a fair representation of the texture. (See, for instance, Arthur Holmes: *Petrographic Methods and Calculations* (D. Van Nostrand Co., 1921), pp. 310–312).

paper gives (for 86 samples) the ratio of the specific susceptibility to the volume proportion of magnetite determined by the area measurements on thin sections. For the 86 samples so calculated, the average value in Grenet's units is 560. Using his value of the average rock density of 2.78, this gives an average value of k' of 0.156. It would be expected that this value is low because of the probability that minerals other than magnetite appear dark in the thin sections and are counted as magnetite, but do not contribute to the susceptibility.

Katô[8] and Nagata[9] have recently published measurements of susceptibilities of lavas around volcanoes in Japan. Chemical analyses of the samples also were made and from them the magnetite content of the rocks was estimated by recasting these analyses into possible mineral content of the rocks by the use of normative minerals.[10] If we accept this determination of the magnetite content, these experiments give another basis for determining the ratio of the susceptibility to the magnetite content and thereby of k'. The individual values from 21 such determinations in Kato's paper and 11 in Nagata's are shown on Fig. 2. The average value of k' determined from Kato's measurements is 0.115 and from Nagata's is 0.116. It will be noticed from Fig. 2 that the samples having maximum susceptibilities approach values of k' of about 0.25. Nagata (p. 124) derives a preferred value of 0.177.

The use of norms to determine magnetite proportions is open to question for two reasons: (1) The minerals derived to fit the chemical composition are not necessarily a unique combination and it is quite possible that part of the Fe_2O_3 and FeO is thrown into magnetite in calculating the norms when it is actually derived from other and non-magnetic minerals. (2) It is pointed out by Nagata that TiO_2 Fe_2O_3 and FeO may exist as a solid solution as titanomagnetite with the Fe_2O_3 in crystal lattices of magnetite which would give minerals much less magnetic than if all the Fe_2O_3 were in pure magnetite. Both of these effects would tend to give values of k' which are too low.

[8] Yosio Katô: *Investigation of the Magnetic Properties of the Rocks Constituting the Earth's Crust (2nd Report), On the Susceptibility of the Rock (Part 1)*. Science Reports of the Tôhuko Imperial University, Sendai, Japan. First Series. Vol. XXIX, No. 4 (May 1941), pp. 602–628.

[9] Takesi Nagata: *Some Physical Properties of the Lavas of Volcanoes Asama and Mihara. II Magnetic Susceptibility.* Bulletin of the Earthquake Research Institute. Tokyo Imperial University, Vol. XVIII (1940), pp. 102–135.

[10] For a general discussion of the use and justification of these normative minerals or "norms," see Holmes, *op. cit.*, p. 412 *et seq.*

All of the above quoted material on the magnetite content and susceptibility of rocks and values of k' derived therefrom is summarized briefly in Table II. The individual magnetite content and susceptibility values (except for Grenet's work for which only the average is given) are shown in Fig. 2.

TABLE II

Author	*Method of Measurement of Magnetite*	*No. of Samples*	*Mean k'*	*Author's Best Value*
Slichter	Magnetic Separator	2	.28	—
Kato	Chem. Analysis ("Norm")	21	.115	—
Nagata	Chem. Analysis ("Norm")	11	.116	.177
Grenet	Thin Section	86	.156	.25

It is unfortunate that Slichter made so few measurements, as his method of magnetite determination is the most direct and would seem to be the most reliable. Considering that both the chemical analysis and thin section methods should be expected to give low values, the experimental work has given approximate confirmation of the expectations from the geometric and demagnetization effects.

DETERMINATION OF AVERAGE MAGNETIZATION AND DENSITY VALUES

The principal hope and purpose of the foregoing investigation was that of developing means by which magnetization and density values of relatively large units of igneous rocks might be estimated. The petrographic literature contains literally thousands of chemical analyses of igneous rocks. The utility of estimating magnetite content from these analyses and thereby calculating magnetization contrasts at first seems very doubtful. However, the Japanese work quoted has indicated that values of magnetite content and resulting susceptibilities derived from chemical analyses are, on the average, within a factor of two of being correct and that these averages are systematically on the low side. Therefore, if we should use average magnetite values, based on chemical analyses, and a value of around 0.12 for k' (see Table II and Fig. 2), the average value of magnetization thus derived for a class of rocks including many samples should be reasonably typical.

The principal sources of available data are H. S. Washington's publications[11] which contain the chemical analyses of many thousands

[11] Henry S. Washington. *Chemical Analyses of Igneous Rocks*, U.S.G.S. Prof. Paper 99 (1917). Also, Henry S. Washington. *The Superior Analyses of Igneous Rocks from Roth's Tabellen*. U.S.G.S. Prof. Paper 28 (1904).

of samples of igneous rocks. For many of these samples the analyses have been recast into the norms, and for a part of the samples the densities are also given. Altogether, there are some 1450 samples for which the densities are given and for which the analyses were

TABLE III

C.I.P.W. CLASSIFICATION
MAGNETITE* AND DENSITY VALUES

Class		*I*	*II*	*III*	*IV*	*V*
No. of Values		*502*	*583*	*283*	*62*	*20*
Minimum	Magnetite	0	0	0	0	0
	Density	2.02	2.35	2.33	2.76	2.87
Maximum	Magnetite	7.4	13.69	18.1	44.54	31.55
	Density	2.83	3.19	3.27	4.34	4.21
Arithmetic Mean	Magnetite	1.75	4.22	5.80	7.44	6.51
	Density	2.60	2.76	2.96	3.17	3.34
Mean Magnetite, % by Volume		0.89	2.28	3.36	4.62	4.26
Median	Magnetite	1.39	3.94	5.34	4.87	4.98
	Density	2.63	2.76	2.96	3.12	3.30
Median Magnetite, % by Volume		0.72	2.13	3.10	2.98	3.22
Mean Deviation from Median	Magnetite	1.03	2.09	2.87	5.29	4.86
	Density	0.07	0.10	0.08	0.16	0.26

*"Magnetite" values are normative magnetite content in % by mass.

complete enough to compute normative magnetite. Each such sample gives a possible value of susceptibility and of density.

There immediately arises a question of how the rocks should be classified. The C.I.P.W. (Cross, Iddings, Pirsson, Washington) Quantitative System of Classification is based on certain arbitrary but definite boundaries determined from the chemical analyses and serves as a straightforward method of classification which divides all igneous rocks into five great classes on the basis of the ratio of salic to femic minerals.[12] This classification has been objected to by

[12] Whitman Cross, Joseph P. Iddings, Louis V. Pirsson, and Henry S. Washington, *Quantitative Classification of Igneous Rocks, Based on Chemical and Mineral Characters, with a Systematic Nomenclature*. Chicago, The University of Chicago Press, 1903.

some petrologists because it does not necessarily reflect the physical or mineral nature of the rocks so that some rocks which appear similar physically and might be given the same or closely allied descriptive names will appear in different classifications, while others which are described as quite different will appear in the same classification.

TABLE IV

IDDINGS CLASSIFICATION
MAGNETITE* AND DENSITY VALUES

Division		*1*	*2*	*3*	*4*	*5*	*6*
No. of Values		*3*	*619*	*565*	*157*	*24*	*82*
Minimum	Magnetite	0	0	0	0	0	0
	Density	2.43	2.02	2.21	2.33	2.54	2.76
Maximum	Magnetite	1.86	16.01	17.86	18.1	10.21	44.54
	Density	2.61	3.27	3.26	3.20	3.20	4.34
Arithmetic Mean	Magnetite	1.01	2.39	4.79	4.43	4.08	7.21
	Density	2.53	2.64	2.83	2.79	2.94	3.21
Mean Magnetite, % by Volume		0.50	1.24	2.66	2.42	2.35	4.54
Median	Magnetite	1.16	1.62	4.41	3.94	3.94	4.87
	Density	2.54	2.65	2.84	2.78	2.94	3.14
Median Magnetite, % by Volume		0.58	0.84	2.46	2.15	2.27	3.00
Mean Deviation from Median	Magnetite	0.62	1.56	2.26	2.77	3.02	5.18
	Density	0.06	0.09	0.12	0.16	0.11	0.19

* "Magnetite" values are normative magnetite content in % by mass.

Another classification by Iddings, also based to some extent on the chemical analysis, is designed to reflect more clearly the petrographic nature of the rocks.[13]

The normative magnetite and density values from the Washington compilations were analyzed statistically according to both classifications. The results are given in Tables III and IV. From the proportion of magnetite indicated by the median value, the intensity of magnetization of the rock has been calculated for each class or division as

[13] For a detailed description of this system, which we shall refer to as the Iddings System of Classification, see Joseph P. Iddings, *Igneous Rocks*. John Wiley & Sons. Vol. I, 1909, Vol. II, 1913, particularly Vol. II.

if magnetized in the earth's field with an intensity of 0.6 Oersted. The results for the two classifications are shown by Tables V-A and VI-A. From the values so calculated, together with the median density, we can calculate both magnetic and density contrasts which might be

TABLE V-A

C.I.P.W. CLASSIFICATION
INTENSITY OF MAGNETIZATION* AND DENSITY VALUES

Class	*I*	*II*	*III*	*IV*	*V*
No. of Samples	*502*	*583*	*283*	*62*	*20*
Median Magnetite Content (% by Volume)	0.72	2.13	3.10	2.98	3.22
Calculated I ($\times 10^6$)	500	1470	2140	2060	2220
Median Density	2.63	2.76	2.96	3.12	3.30

TABLE V-B

MAGNETIZATION AND DENSITY CONTRASTS
Upper figure is magnetization contrast (in C.G.S. Units $\times 10^{-6}$)
lower is density contrast (in grams per c.c.)

		Intrusive Class				
		I	*II*	*III*	*IV*	*V*
Intruded Class	I	0 0	+970 +0.13	+1640 +0.33	+1560 +0.49	+1720 +0.67
	II	−970 −0.13	0 0	+670 +0.20	+590 +0.36	+750 +0.54
	III	−1640 −0.33	−670 −0.20	0 0	−80 +0.16	+80 +0.34
	IV	−1560 −0.49	−590 −0.36	+80 −0.16	0 0	+160 +0.18
	V	−1720 −0.67	−750 −0.54	−80 −0.34	−160 −0.18	0 0

* Intensity of Magnetization Values ("Calculated I") are calculated for an assumed magnetizing field of 0.6 Oersted and susceptibility of 0.116 times the median volume content of magnetite.

expected from various combinations of intrusion of one type of igneous rock into another and these contrasts are indicated by Table V-B for the C.I.P.W. classification and Table VI-B for the Iddings classification.

Although the range of values within any one class or division is discouragingly large and there are overlaps of both density and magnetite from one group of samples to another, still the average magnetite values proceed in a quite regular order especially through the Iddings

TABLE VI-A

IDDINGS CLASSIFICATION
INTENSITY OF MAGNETIZATION* AND DENSITY VALUES

Division	*1*	*2*	*3*	*4*	*5*	*6*
No. of Samples	*3*	*619*	*565*	*157*	*24*	*82*
Median Magnetite Content (% by Volume)	.58	.84	2.46	2.15	2.27	3.00
Calculated I ($\times 10^6$)	400	580	1700	1480	1570	2070
Median Density	2.54	2.65	2.84	2.80	2.94	3.14

TABLE VI-B

MAGNETIZATION AND DENSITY CONTRASTS
(Upper figure is magnetization, contrast lower is density contrast)

		Intrusive Division					
		1	*2*	*3*	*4*	*5*	*6*
Intruded Division	1	0 0	+180 +0.11	+1300 +0.30	+1080 +0.26	+1170 +0.40	+1670 +0.60
	2	−180 −0.11	0 0	+1120 +0.19	+900 +0.15	+990 +0.29	+1490 +0.49
	3	−1300 −0.30	−1120 −0.19	0 0	−220 −0.04	−130 +0.10	+370 +0.30
	4	−1080 −0.26	−900 −0.15	+220 +0.04	0 0	+90 +0.14	+590 +0.34
	5	−1170 −0.40	−990 −0.29	+130 −0.10	−90 −0.14	0 0	+500 +0.20
	6	−1670 −0.60	−1490 −0.49	−370 −0.30	−590 −0.34	−500 −0.20	0 0

* Intensity of Magnetization Values ("Calculated I") are calculated for an assumed magnetizing field of 0.6 Oersted and susceptibility of 0.116 times the median volume content of magnetite.

classification, while the density values proceed regularly through the C.I.P.W. classification, as would be expected from its chemical basis.

From magnetic surveys, it is possible to estimate magnetic contrasts from the form and relief of magnetic anomalies, together with an estimate of the depth to the top of the magnetic (*i.e.*, igneous) material. A number of contrasts thus estimated[14] are given in Table VII.

TABLE VII

MAGNETIZATION CONTRASTS DERIVED FROM MAGNETIC SURVEYS

Location	*No. of Anomalies Averaged*	*Average Magnetic Relief (Gammas)*	*Average Estimated Magnetization Contrast* ($\times 10^6$)	*Range Mag. relief*	*Range Magnetization Contrast*
Eastern Wyoming	3	65	300	50–80	210–460
Eastern Wyoming	5	260	1040	210–300	600–1400
Eastern Wyoming	1	740	2500	—	—
West Texas	4	160	620	100–175	380–800
West Texas	6	240	840	210–300	500–1200
West Texas	3	500	1700	400–550	1300–2100
West Texas	1	1100	4500	—	—
Crosbyton High	1	3000	6700	—	—
Mississippi	4	230	1430	200–270	900–2600
Mississippi	6	410	1530	300–500	1070–2000
Mississippi	1	850	4120	—	—
Central America	1	320	900	—	—

The range of contrasts of Table VII includes many values generally within the range of the calculated contrasts of Table V-B and VI-B, but the average values from actual surveys are substantially higher. This is especially true when one considers that the most common contrasts presumably would be those relatively low values between adjacent or nearly adjacent classifications (*i.e.*, the spaces next to or near the zero-contrast diagonal in tables V-B and VI-B). One might guess that the calculated values should be increased by a factor of about two to be generally in accord with those derived from the surveys. Considering the very wide ranges of individual values, and the fact that the factor for k' (*i.e.*, the value 0.116) is based on only two series of measurements (*i.e.*, the Japanese work) on rocks from a restricted locality and of restricted classifications, the apparent discrepancies are not surprising. If the magnetite norm from chemical

[14] These estimates were calculated by Mr. James Affleck at the Gulf Research Laboratory, to whom grateful acknowledgment is hereby made.

analysis is, on the average, quite representative of actual magnetite in the rock, the factor for k' should approach the theoretical value of around 0.25, and the agreement would be much improved. When and if further work develops a better basis for evaluating k' on the basis of chemical analysis, new values for magnetization values and contrasts, corresponding to those of tables V-A and -B and VI-A and -B could be calculated very simply.

A possibly important factor which has not been included is the contribution of remanent or permanent magnetization to the total magnetization of the rocks. The geometric and demagnetization factors and the calculation of magnetization from magnetite content, of course, are concerned only with the induced part of the total magnetization. There has been considerable work[15] on the measurement of remanent magnetization and its causes, which indicates that this part may be as large or larger than the inductive magnetization. If, as seems probable, the remanent magnetization were established at the time of cooling of the rocks, its intensity and direction would be controlled by the magnitude and direction of the earth's field at the time and place of cooling, which may or may not be similar to that of the present time and present position of igneous rock masses. We might guess that the remanent component, on the average, is of the same order of magnitude and more or less in the same direction as the induced component. Such a condition may be an explanation of the fact that the values of induced magnetization calculated from values of magnetite content are generally smaller than those shown by analysis of magnetometer surveys.

A calculation of density contrasts from gravimetric surveys to check those indicated by V-B and VI-B is not feasible, because, usually, a gravity anomaly can indicate only the total mass anomaly and the density contrast is unknown, for the required other data to give the boundaries or size of the mass anomaly are rarely available. On the other hand, the density and density contrast data of the tables

[15] J. G. Koenigsberger. *Die Abhändigkeit die natürlichen remanenten Magnetisierung bei Eruptivgesteinen von deren Alter u. Zusammensetzung.* Beit. z. Ang. Geophys. 5 (1935), pp. 193–246. Also see Terr. Mag. and Atmos. Elec., Vol. 43, Nos. 2–3 (1938).

H. Reich. *Über die natürliche Magnetisierung von Gesteinen auf Grund von Messungen von Bohrkernen.* Beit. z. Ang. Geophys. 9 (1941), pp. 49–64.

Takesi Nagata. *The Mode of Causation of Thermo-Remanent Magnetism in Igneous Rocks. Preliminary Note.* Bulletin of the Earthquake Research Institute, Tokyo Imperial University, Vol. XIX, No. 1 (March 1941), pp. 49–81.

are much more direct so that there is little reason to question their significance.

Certain general conditions are to be expected if the density and magnetic values and contrasts of the tables can be considered as broadly characteristic of the different classifications of igneous rocks:

(1) In general, heavier rocks are more magnetic.

(2) If the basement rocks tend to be stratified according to density with heavier ones below and lighter ones above, intrusions of the lower into the higher rocks should produce positive gravity anomalies and positive magnetic anomalies, and downthrusts of upper into lower rocks should produce negative gravity anomalies and negative magnetic anomalies.

(3) Corresponding magnetic and gravity anomalies of opposite signs (*i.e.*, magnetic high and gravity low, or *vice versa*) would be expected only rarely, as the tables indicate only two cases (*i.e.*, an intrusion of C.I.P.W. class 4 into class 3, or of Iddings' division 5 into division 3) which would suggest such a circumstance.

The above expectations are based on the assumption that the igneous activity which produces the deformations of the earth's crust responsible for magnetic and gravity anomalies affects masses of rock whose physical differentiation involves properties which are parallel to those on which the rock classifications are based. For the C.I.P.W. system the regular progression of density through the different classes indicates a fundamental parallelism, and since density may control stratification, the roughly parallel increase in magnetite concentration may be a useful generality.

In cases where magnetic and gravity anomalies are roughly coextensive, the order of magnitude of the contrasts which appear reasonable from the foregoing tables may serve to give rough limits to postulated forms from which geophysical effects may be calculated to explain observed effects. When, as is usually the case, such calculations must be based entirely on speculation, with no specific factual data for the particular case or area, the order of magnitude of reasonable contrasts, indicated by this work, may serve to control what might otherwise be very wild guesses.

There are individual cases in which a large gravity anomaly of almost unquestioned basement origin exists without a corresponding magnetic anomaly, or *vice versa*. Such cases must involve bodies of rock which do not behave according to the classes and divisions on

which the tables are based. However, the wide range of the ratio of contrasts, which is indicated by the pairs of values in tables V-B and VI-B, indicates that agreements of anomalies might range from very obvious to very obscure.

Any common boundaries of magnetic and density contrasts can persist only to the depths to which the rocks are still magnetic. The Curie point of magnetite is around 475°C., a temperature which would be expected to be reached at depths of the order of some 10 to 20 miles.[16] Vacquier and Affleck[17] made a statistical evaluation of this depth from magnetic anomalies and determined that the base of the anomalies and presumably the depth of the temperature of the Curie point is around 12 miles below the surface. The same limitation does not apply to density contrasts and corresponding gravity anomalies. Therefore, broad, regional gravity features which may arise from density contrasts at depths greater than some 10 to 15 miles would not be expected to have corresponding magnetic features.

The authors are indebted to Dr. Paul D. Foote and Dr. E. A. Eckhardt for permission to publish this paper.

DISCUSSION

This excellent article is an ingenious approach to a very pertinent problem. However, there are many pitfalls in the computations of "norms" which should be pointed out. In this computation, it is largely a matter of chance that there is any resemblance between the calculated minerals—the "norms"—and of the actual minerals—the "mode." It should be noted that the physical properties of a rock are determined by the mode rather than the norm. In Clark's *Data of Geochemistry* (Frank Wigglesworth Clark. The Data of Geochemistry, U.S.G.S. Bul. 770 (1924), pp. 432) the mineralogic irregularities introduced by the calculations of norms are illustrated by Table I.

Clark further states that "In calculating the percentage of a mineral from the proportions of oxides shown by analysis there is a strong tendency toward a multiplication of errors. The computed mineral composition of a rock is incorrect by multiples of the errors existing in the analysis. and these may be, in fact are, sometimes large." In all fairness to the method, however, it should also be stated that in some instances the mode and the norm of a rock are almost identical. Mineral compositions vary greatly, and alteration caused by weathering, heat, hydrothermal action, or metamorphism may cause extreme differences in magnetic properties. For example, pyrite loses sulphur and changes to pyrrhotite at 665°C., becoming a black magnetic mass.*

[16] A. E. Benfield. *Thermal Measurements and Their Bearing on Crustal Problems.* Am. Geophys. Union, Trans. of 1940. Part II, pp. 155–162.

[17] Victor Vacquier and James Affleck: *A Computation of the Average Depth to the Bottom of the Earth's Magnetic Crust, Based on a Statistical Study of Local Magnetic Anomalies.* Transactions of 1941 of the American Geophysical Union, pp. 446–450.

* Winchell, A. N. *Elements of Optical Mineralogy*, Vol. III, p. 22.

TABLE I

COMPOSITION OF BUTTE GRANITE

Norm			*Mode*		
Quartz	19.38		Quartz	22.86	
Orthoclase	25.02		Orthoclase	18.35	
Albite	23.58	66.67	Albite	23.06	58.09
Anorthite	18.07		Anorthite	16.68	
Diopside	.67		Biotite	10.92	
Hypersthene	6.78	7.45	Hornblende	3.56	14.48
Magnetite	3.01		Magnetite	1.86	
Ilemenite	1.22	4.23	Ilmenite	.46	2.32
Pyrite	.24		Pyrite	.24	
Apatite	.31	.55	Apatite	.31	.55
Etc.	.99		Etc.	.85	
	99.27			99.15	

These objections are well illustrated by Tables III and IV of the paper under discussion, in which the mean deviation of the normative magnetite is in many cases larger than the mean magnetite content.

If the susceptibilities of igneous rocks are to be determined by analysis with chemical and optical means, a more effective system would be to use a Rosiwal analysis of thin sections and a heavy mineral and magnetic separation with a chemical analysis of the magnetic minerals only. This combination would give a better indication of the true mineralogy and would aid in distinguishing the less-magnetic titaniferous magnetite from true magnetite.

The process of magmatic differentiation should also be considered. In general, the iron-magnesium minerals and magnetite, which are the first to crystallize out of the magma, are more or less localized around the borders of an igneous mass. This would tend to give higher magnetic and gravity anomalies near the borders of an igneous mass. This does not hold in the case of aphanitic rocks, however, which rarely show connected series.

The authors' avowed purpose on page 10 in this article is "to find some means by which magnetization and density values of large units of igneous rocks might be estimated," and they have succeeded to a great extent. However, in view of the many factors and assumptions which are inexact or theoretical in the calculation of the magnetism a more practical method of deriving this end might be in the use of a direct measurement of the susceptibility with a device such as that described by William M. Barrett, "A Method for Determining Magnetic Susceptibility of Core Samples." A.I.M.E. Geophysical Prospecting, 1932, pp. 216.

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AUTHORS' REPLY

We are very glad to receive a petrologist's generally favorable comments on our paper. Perhaps, in our extremely limited petrographic knowledge, we have "rushed in

where angels fear to tread," although not without some appreciation of the pitfalls in our path. Our excuses are, first, that to a certain extent, these pitfalls may be bridged by a broad statistical base and second, that our aim has been to find a way of making a geophysical application of the great body of existing fact in petrographic literature rather than to make new measurements of the particular properties discussed. Since we agree with most of the criticisms stated, apparently we did not emphasize certain points as much as may be desirable and, therefore, we shall take this opportunity to explain some details more fully.

RELATION BETWEEN NORM AND MODE

It is realized that the "norm" and "mode" are not necessarily identical. The mode is the expression of the actual mineral content, based on some method of isolation and identification of the mineral grains present. The norm is based entirely on the chemical analysis and is computed by a standardized procedure, designed with the hope of approximating to the mineral content. As to the relations between the norm and the mode for the classifications we have used, we shall quote from pp. 151–152 of the reference listed in footnote 12:

"It is obvious that no one systematic method of calculation of mineral composition from the chemical can correspond with all the varying possibilities of actual mineral development. The method adopted by us, however, being founded on the most frequently observed mineral relations in igneous rock and on the most generally applicable principles, should yield norms which correspond with the mode in the majority of cases.

"This is a point which can only be tested by appeal to the literature of petrography, and comparison of the calculated norms with the modes as furnished by the descriptions. We have, it may be stated here, tested our proposed method in regard to this point very thoroughly upon many hundreds of rock analyses, and especially by means of a collection made by one of us (H.S.W.) of all analyses of igneous rocks which have been published since 1883, amounting to over three thousand.

"This comparison shows that the accord between norm and mode is complete or nearly so in the very great majority of rocks of Class I and in the greater portion of those of Class II, these two classes comprising over three-quarters of the known or analyzed igneous rocks of the globe. The accord is also very good in Class V, which includes but few rocks. Classes III and IV show less constant accord, as is to be expected in view of their composition. The results of our proposed method of calculation may therefore be regarded as satisfactory."

THE TWO CLASSIFICATIONS USED

The preceding quotation refers to the Classes of the C.I.P.W. classification. It also applies to the Iddings System of Classification, since the latter can be approximately defined in terms of the C.I.P.W. system. Iddings' system was devised to reflect more clearly the petrographic nature of the rocks than the C.I.P.W., for convenience in field work, but still involved the chemical analysis.

We have neglected all but two of the many systems of classification proposed, because for most systems the number of rock analyses worked out according to the principles of the classification is too small for valuable results to be expected from the type of statistical analysis we have applied.

STATISTICAL BASIS OF THE METHOD

We agree that the best method of determining the susceptibility is by direct measurement and that the best method of mineral analysis is the direct one. But just as the norm system was devised to yield an approximate mineral analysis for cases in which the latter had not or would not be carried out, so this statistical study was made in the hope of reaching approximate values for the vast number of analyses of rocks, whose susceptibilities had not been measured or would not be measured.

We wish to emphasize that the study has been a statistical one, based on the use of a large number of samples. Thus, we hoped that the admittedly large discrepancy which may occur between the mode and norm for any one sample, such as the one quoted by Mr. Reno, might be balanced by a discrepancy in the opposite direction for another sample and that on the average the results might be valid, in a way quite parallel with the tests mentioned by Washington in the foregoing quotation.

As a measure of the scatter of the values, the mean deviation from the median is used, which is the proper statistical measure of scatter for use with the median. If the distributions were of the normal Gaussian form (which they are not), the arithmetic mean and the median would be the same and the probable error would be about 0.85 of the mean deviation, which facts may help somewhat in visualizing the reliability of the computed averages.

It should be noted that the mean deviations for the magnetite in Tables III and IV are for the median mass percentages, not the median volume percentages (which latter were computed directly from the median mass percentages and median densities, taking the density of magnetite as 5.1). A glance at Tables III and IV will show that, contrary to the statement made in the preceding criticism, there is only one case in each table (i.e., C.I.P.W. Class IV and Iddings division 6) for which the mean deviation is greater than the median and these two cases occur in instances where the number of available samples was smaller than was desirable for this statistical study.

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CORRELATION OF GRAVITY OBSERVATIONS WITH THE GEOLOGY OF THE SMOOTHINGIRON GRANITE MASS, LLANO COUNTY, TEXAS*

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ABSTRACT

Gravitational observations were made, and the geology mapped, on the Smoothingiron granite mass in Llano County, Texas. The observed gravitational anomaly was interpreted to give depth and a subsurface shape for the mass. Maps are provided showing the gravity contours and the geology, and geological and mathematical appendices are added.

INTRODUCTION

The gravitational effects of the Smoothingiron granite mass were first noticed by the authors in the course of an investigation of the Iron Mountain magnetite deposit.[1] The gravitational anomaly associated with this magnetite deposit is superimposed on a strong regional gradient, and it was hoped that additional observations of the gravitational force would suggest a connection between the regional gradient and the rocks of the basement complex. When the gradient was followed southwest from Iron Mountain across the Smoothingiron granite mass a gravity low was found, which appeared to be centered on the granite mass as it is mapped on Spencer, Paige, and Kay's geologic map of the region.[2]

The correlation thus indicated between the granite mass and a gravity low naturally invited further study, and offered a specific problem for attack. Gravity stations were accordingly laid out at about quarter-mile intervals on the roads crossing the mass, and the net of stations was extended in all directions away from the mass a sufficient distance to define its gravitational anomaly. The geology of the area was remapped, using aerial photographs as a base, by Dr. Barnes, who also measured the positions and elevations of the gravity stations; the observations of the gravitational force were made and interpreted by Mr. Romberg.

* Presented at the annual meeting, Fort Worth, Texas, April, 1943.

† La Coste and Romberg, Austin, Texas.

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[1] Barnes, V. E. and Romberg, Frederick. *Gravity and magnetic observations on the Iron Mountain magnetite deposit*, Llano County, Texas. GEOPHYSICS, Vol. 8, pp. 32–45, 1943.

[2] Paige, Sidney. *U. S. Geol. Survey Atlas*, Folio No. 183, Llano-Burnet Folio, 1912.

DESCRIPTION OF THE SMOOTHINGIRON GRANITE

The Smoothingiron granite mass is located in northwestern Llano County and is centered about four miles due west of Valley Spring. It takes its name from Smoothingiron Mountain, which is a flat-topped hill rising about 540 feet above the level of Cold Creek, which flows along its western base. The granite mass is somewhat elliptical in shape, about 4 miles wide in an east-west direction and about 5 miles long. The granite is coarse-grained and equigranular except for a small area near the center which is porphyritic.

The border of the granite was carefully mapped and examined for features that might reveal something about the shape of the mass. Inclusions are absent and the feldspars are mostly unoriented. Keppel[3] noted that the "Flow structure is indistinct, and the rock is quite massive." Pegmatites and aplites within the mass are extremely rare and nothing could be determined about the probable subsurface shape of the granite mass from these criteria. Ring dikes of Smoothingiron granite, somewhat finer-grained, are parallel to the edges of the main granite mass to the south and east. The position of these dikes indicates that the cross section of the main granite mass becomes larger with depth at least on the southern and eastern sides of the mass.

The granite is of pre-Cambrian age and is emplaced in older sedimentary rocks, now metamorphosed, which have been designated by Paige[4] as the Valley Spring gneiss and the Packsaddle schist. These rocks have a higher density than the granite. The Valley Spring gneiss, in 25 samples, averaged 2.64, and 8 samples of Packsaddle schist averaged 2.95. Seven granite samples ranged in density from 2.59 to 2.65 and averaged 2.62.

GRAVITY OBSERVATIONS

The observations of the gravitational force were reduced in the usual manner for latitude and elevation. A combination Bouguer and free air elevation correction of 0.06 mg/ft. was used, which corresponds to a density of 2.46 gms/cm^3. Terrain corrections were not made, since local topographic irregularities were small except on the extreme north end of the prospect. Tie-ins and check readings showed that the probable error of any station with respect to any other was

[3] Keppel, David. *Concentric patterns in the granites of the Llano-Burnet Region, Texas.* Bull. Geol. Soc. America, vol. 51, p. 991, 1940.

[4] Paige, Sidney, *op. cit.*, pp. 3–4, 1912.

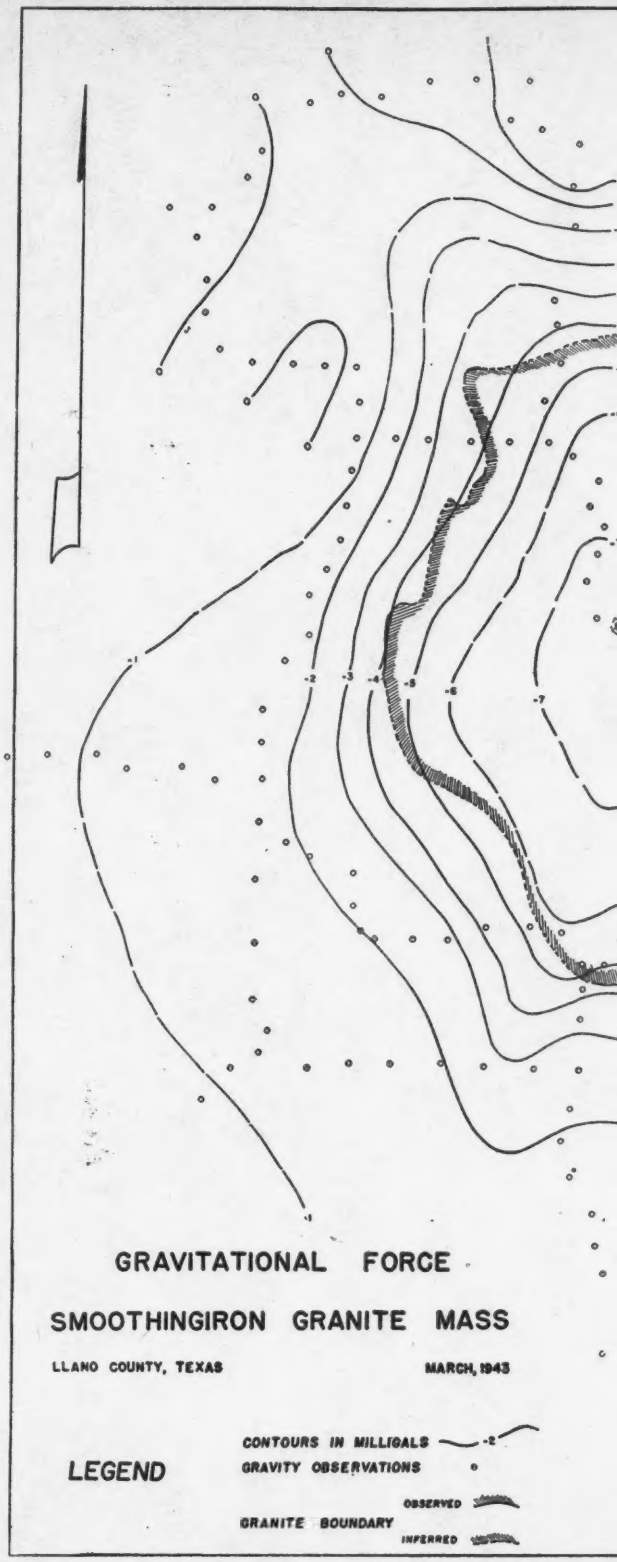
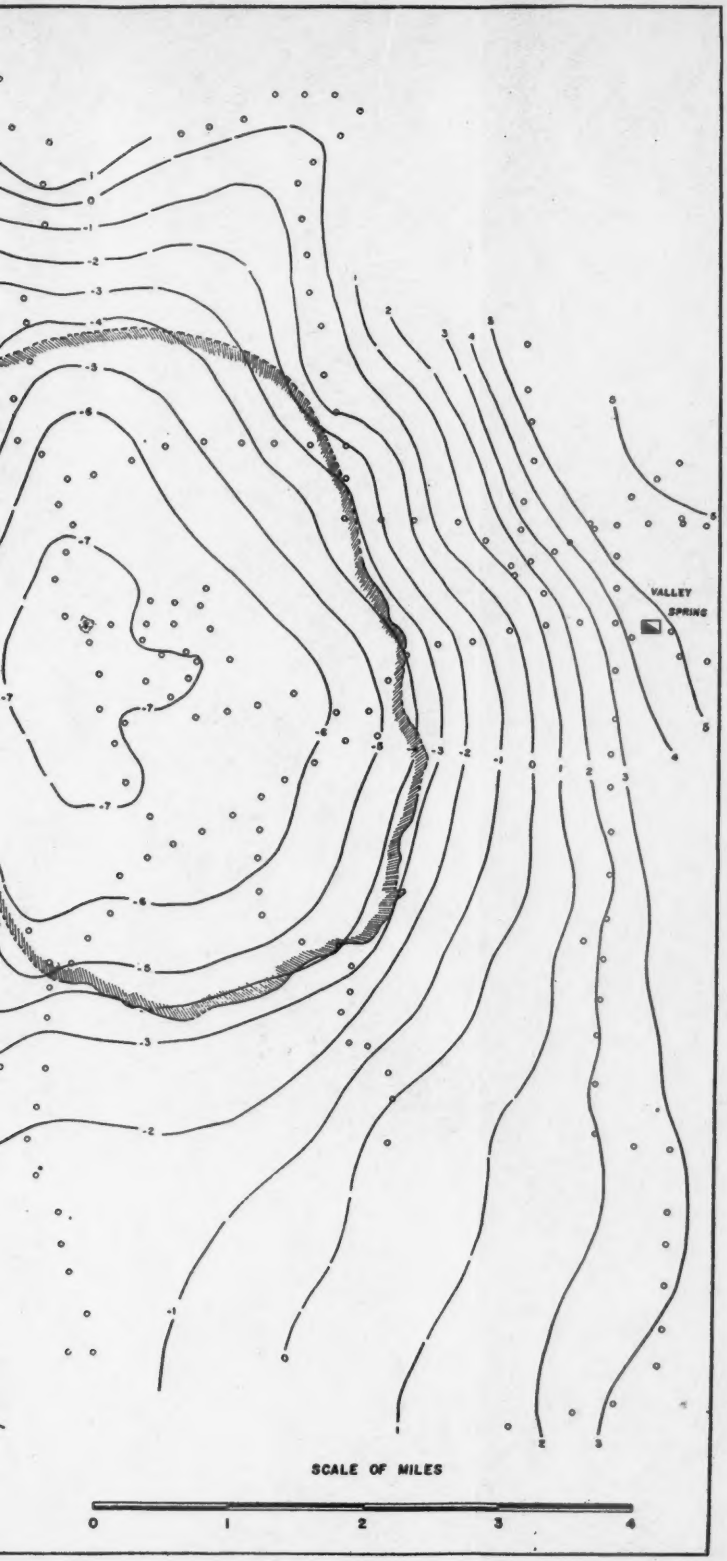


FIG. 1. Gravity map and outline of the Smoothingiron granite mass
of the granite mass is shown by heavy line with side h



nite mass, Llano County, Texas. Contour interval is 1 mg. Observed boundary
th side hatchuring; inferred boundary by heavy dashed line.

less than one-tenth milligal, which is small enough considering the size of the anomaly.

The locations of the stations, and the contour lines for the force, are shown on Fig. 1. The outline of the granite mass has been drawn on the same figure, so that the relation of the granite to the gravitational anomaly can be plainly seen. In general the contours are circular in shape, forming a large minimum which is concentric with the granite mass. The gravity minimum flattens out in all directions at a distance of two miles or so from the edge of the granite to a background value some six or seven milligals higher than the minimum. The anomalous figure is generally symmetrical except to the northeast, where the background value appears to be four milligals or so higher than elsewhere. The most interesting qualitative fact about the gravitational picture is the way in which the contours follow the edge of the granite. In general the edge of the mass is delineated by the minus-four contour. This contour swings inward from the edge on the northeast sector, and outward from it in the southwest, but these swings appear to be associated with respectively higher and lower background values. (See Fig. 1 and Geologic Appendix.)

INTERPRETATION OF GRAVITY DATA

The problem of interpreting the gravitational picture was approached as usual by making a set of simplifying assumptions. It was assumed, first, that the rocks on top of the granite (see Geologic Appendix) were not thick enough so that they had to be taken into account, and, second, that the granite itself was a mass of homogeneous density and simple shape. It was assumed further that the shape of the anomaly in all directions except the northeast was typical of the mass, and that the higher background values of the northeast sector were due to denser country rock—that is, to an independent positive anomaly, such as a preponderance of schist over gneiss—rather than to an irregularity in the shape of the mass. (This assumption is supported by the quantitative findings and will be referred to below.)

Under the above assumptions the questions about the granite mass which might be answered by the gravity data are as follows: First, how thick is the granite? Is it a thin body overlying a considerable thickness of metamorphic rocks, or is it a thick body extending downward to a great depth, such as postulated by Keppel?[5] Second,

[5] Keppel, David, *op. cit.*

what is the shape of the granite mass underneath the surface? Does the boundary between the granite and metamorphics go inward at depth, or outward, or straight down?

Fig. 2 shows cross sections of the observed force in three directions outward from the center. The northeast section shows clearly the

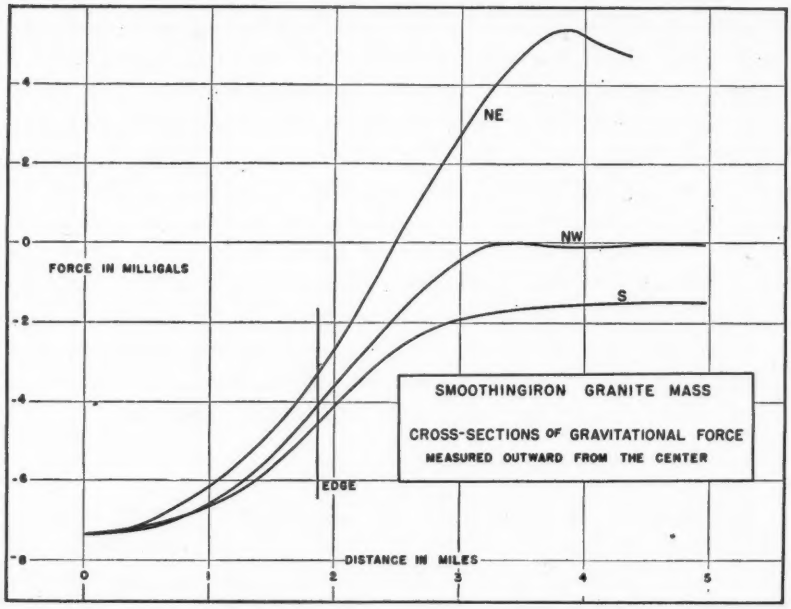


FIG. 2. Cross sections of observed gravity in three directions from the center, Smoothingiron granite mass, Llano County, Texas. Location of observed edge of granite mass is shown by vertical line.

higher background value as previously described, but it is noticeable that it appears to flatten off at about the same distance from the center as the other two sections do. In addition, the slope of each curve at the edge is roughly proportional to the total change in force from center to background. In other words, the cross sections are geometrically similar. This can be taken, qualitatively, to mean that the mass is roughly radially symmetrical, and is not likely to be, say, an intrusive body with parallel sloping sides. Its lateral boundaries ought to have somewhere nearly the same slope, whether it is outward, inward, or vertical, anywhere along the edge.

The question of the actual shape of the mass—the depth of its floor

and the slope of its sides—can be approached only through quantitative considerations. A model was accordingly set up for the purpose of comparing the gravitational effects of hypothetical masses with that of the observed mass. The most convenient model to choose is of course an upright cylinder with horizontal upper and lower boundaries (see Fig. 3) having a radius of, say, 3 km, and an unknown depth. The downward attraction of such a cylinder is then computed for different depths (see Mathematical Appendix) and the results compared with the observed force. If the density difference between the granite and the surrounding rocks were known, the depth could be found simply, but since the direct measurements of density (see Geological Appendix) do not give a convincing value the density difference must be treated as an unknown. In computing the force curves for the hypothetical cylinders, a density difference was chosen for each depth which "normalized" the minimum force and made it equal to the observed minimum.

The similarity in shape of the observed cross sections (Fig. 2) made it possible to draw a characteristic cross section which was typical of the observed force. Since it is a generalized curve only its broad features, such as its height where it crosses the edge of the mass, and the position of its upper "corner" (point of maximum curvature) can be taken to mean anything quantitatively, though its relative shape ought to be correct to, say, plus or minus a quarter milligal. Fig. 4 shows such a composite cross section of the observed force, and, for comparison, curves of the hypothetical force for depths of 1 km, 2 km, and infinity. The curves are, from the center of the mass to its edge, close enough together so that no information can be got by comparing them in that region, though the infinity-curve is far enough away from the others to suggest that the mass is not very deep. On the other hand, the upper corners of the curves are well separated. The computed curves show that the distance from the background value to the corner can be taken as an index of the depth. On this basis the granite appears definitely to have a shallow bottom—of the order of one km.

The positive anomaly to the northeast can most easily be explained by saying that it is due to country rock which is heavier there than on other parts of the prospect. If this anomaly were caused by asymmetry in the shape of the granite rather than by extra dense country rock, the geological picture would be complicated and difficult to reconcile with the observed surface geology. Study of the composite

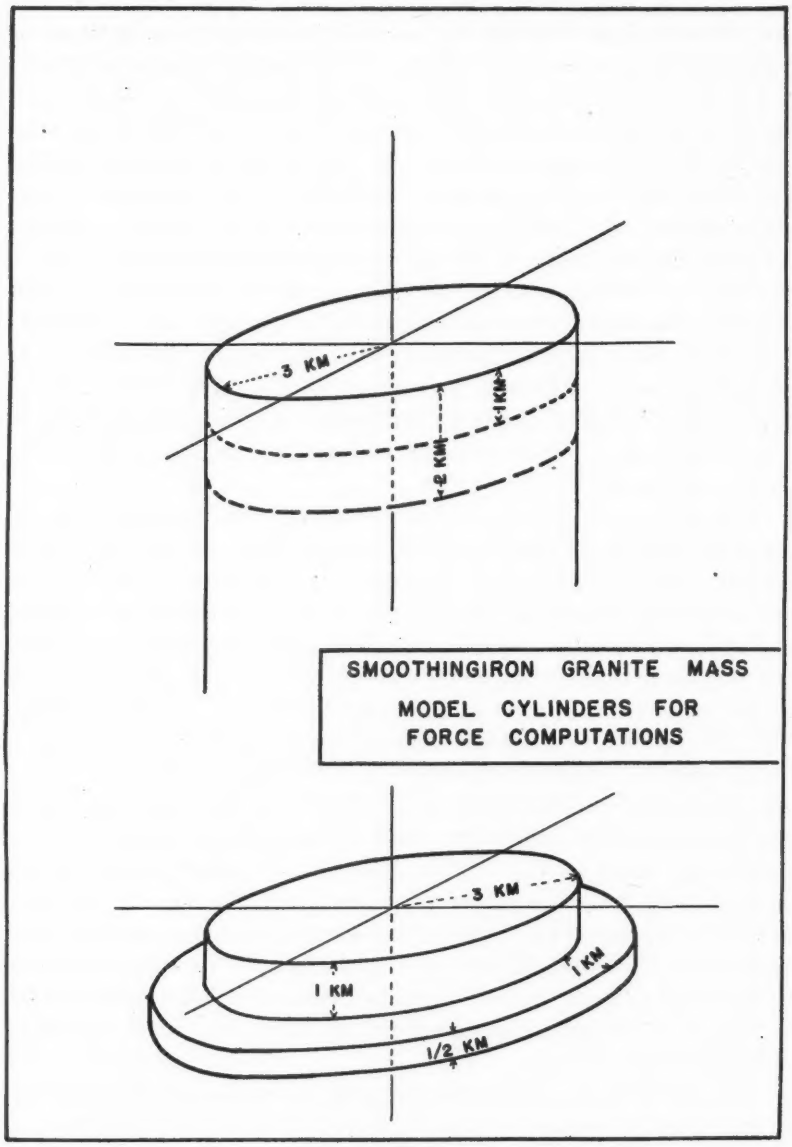


FIG. 3. Simplified hypothetical models of the Smoothingiron granite mass used for computing gravity for comparison with observed gravity.

cross section yields one other piece of information. The corner of the observed force is a good half mile outward from the corners of the computed forces for 1 and 2 km. This shows that the effective edge of the mass must be some distance outward from the visible edge—in

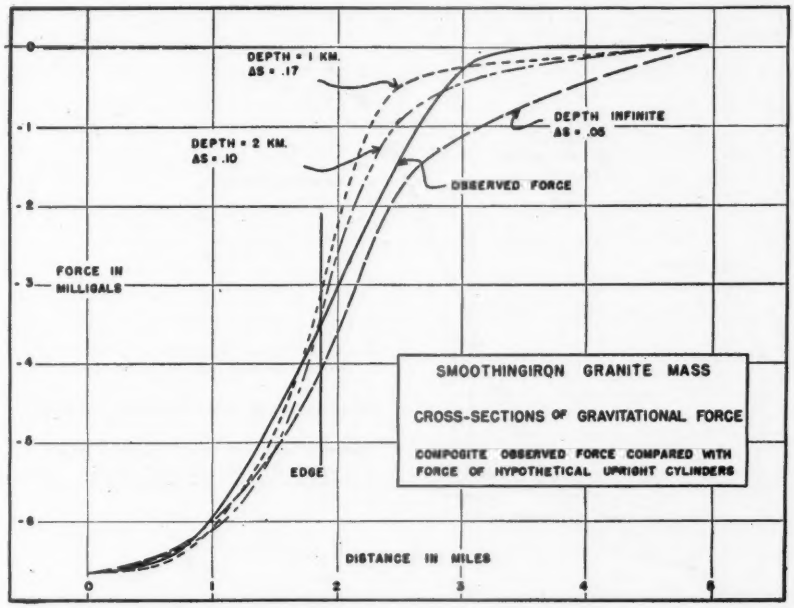


FIG. 4. Generalized observed gravity profile of Smoothingiron granite mass (solid line) compared with gravity computed from cylinders 1 km deep with $\Delta s = 0.17$ (dotted line); 2 km deep with $\Delta s = 0.10$ (dash-dot line); infinitely deep, and with $\Delta s = 0.05$ (dashed line). Location of observed edge of granite mass is shown by vertical line.

other words, that the boundary of the mass slopes outwards. To illustrate this conclusion quantitatively, a model was assumed which consisted of the original 1-km-deep cylinder, with another cylinder coaxially under it whose radius was four km and which was $\frac{1}{2}$ km thick. (See Fig. 3). The new model, with a normalizing density of 0.13 (which according to the measured density data is a perfectly acceptable value), gives a computed curve which does not differ from the generalized force curve anywhere by more than 0.3 mg. (See Fig. 5.) It would clearly be idle to refine the computations further. It appears therefore that the mass probably has a depth of some $1\frac{1}{2}$ km, and the

shape (to smooth out the model) of a truncated cone, whose base is something like 1 km greater in radius than its upper boundary.

The final model for the shape of the mass does not take into account the possible presence of a feeder. Unless such a feeder were very

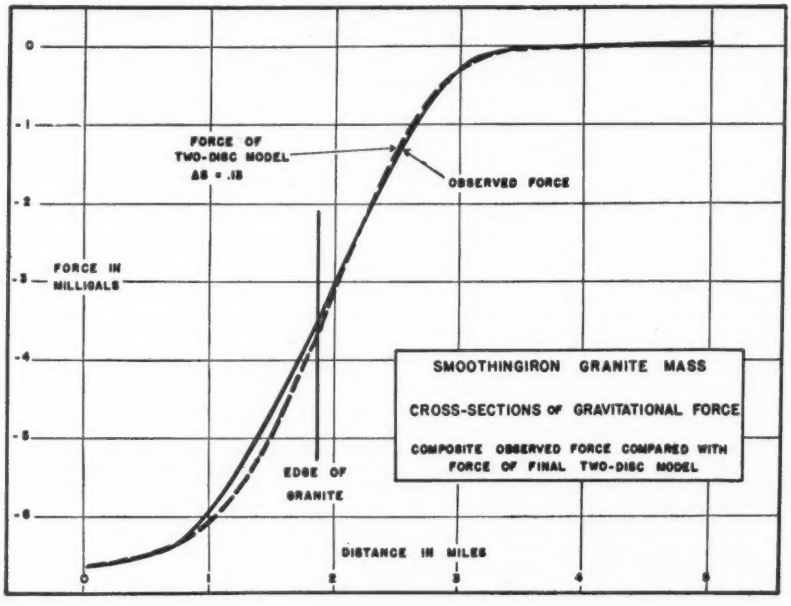


FIG. 5. Generalized observed gravity profile of Smoothingiron granite mass (solid line) compared with gravity computed from two cylinders, upper with 3 km radius and 1 km thick, lower with 4 km radius and 0.5 km thick (dotted line). See lower illustration in Figure 3. Location of observed edge of granite is shown by vertical line.

thick, or the granite itself were much thinner than it is, it would not be possible to differentiate between the effect of the feeder and that of the mass itself.

EFFECT OF A BURIED MASS

The study of the granite mass, as granite, is of course not significant to petroleum prospectors except as a type problem of quantitative gravitational effect. However, it has been noted in various discussions that a map of the gravitational force in a sedimentary region has a tendency to show large-scale anomalies which do not appear to be connected with sedimentary oil structures. The granite mass de-

scribed in this paper would, if it were covered with horizontally uniform sediments to a depth of, say, two kilometers, still show a large closed anomaly. Fig. 6 shows a cross section comparing the observed anomaly and the approximate gravitational effect such a mass would

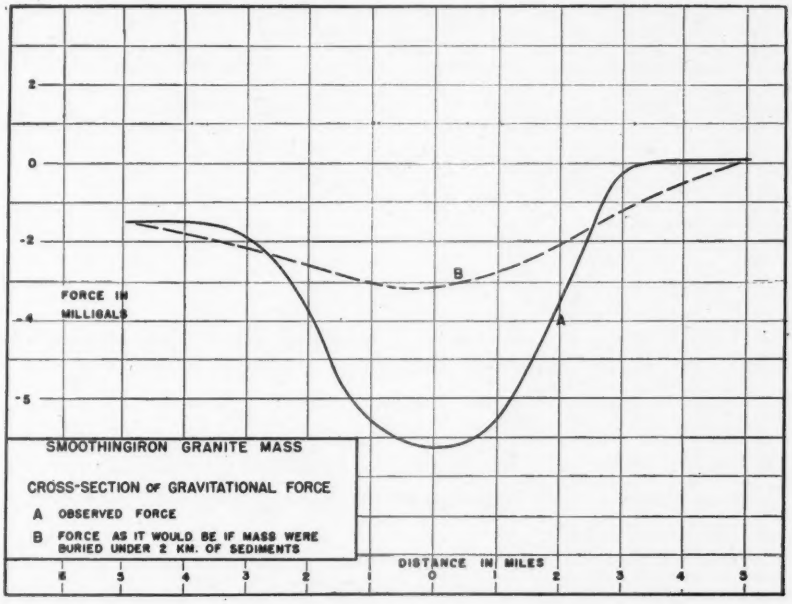


FIG. 6. A. Observed gravity profile across Smoothingiron granite mass (heavy line). B. Gravity profile of Smoothingiron granite mass as it would be observed if it were covered by 2 km (6600 feet) of horizontally stratified sediments (dashed line).

have if it were covered 2 km (6600 ft.) deep with neutral material. It is clear that such anomalies must be taken into account by petroleum prospectors. This raises the question of how to differentiate between basement anomalies and sedimentary ones, and the further question of how much correlation there may be between the two kinds of anomalies in regions with different geologic histories.

GEOLOGIC APPENDIX

A geologic map was made of the Smoothingiron granite and of the surrounding and overlying rocks, Fig. 7. Much of the geological detail contained on this map, excepting the pre-Cambrian geology, is not pertinent to the gravity interpretation, but some of the features shown

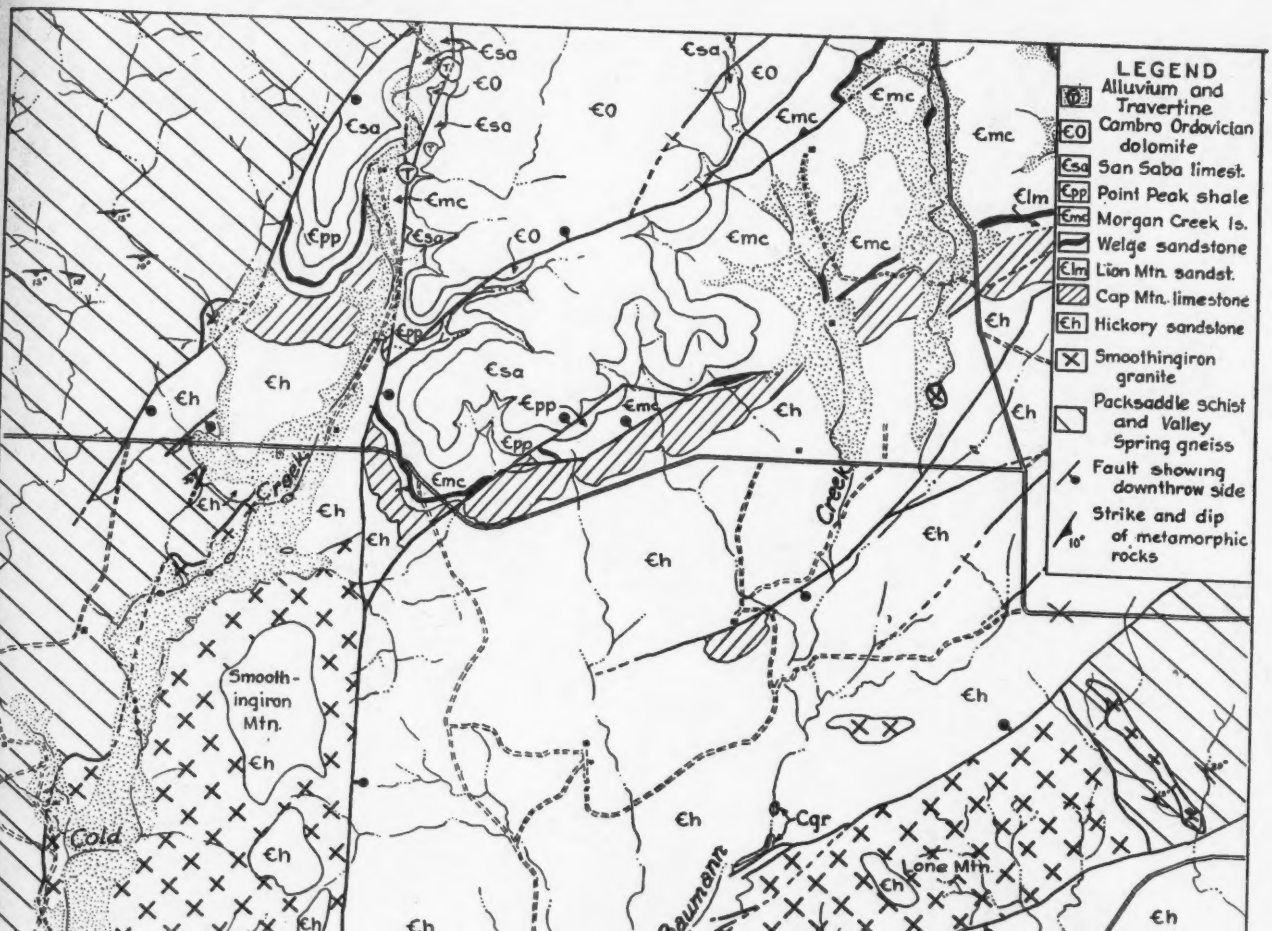
apparently have a slight effect. The Smoothingiron granite is in part covered by Paleozoic sedimentary rocks which have concealed about half of the granite boundary, necessitating an estimation of the position of the covered portion of the boundary. The Paleozoic stratigraphic column of the area is as follows:

System	*Formation*	*Member*
Ordovician	Ellenburger	An unnamed dolomite
Cambrian	Wilberns	Pedernales dolomite[6]
		San Saba limestone[6]
		Point Peak shale[6]
		Morgan Creek limestone[6]
		Welge sandstone[6]
		Disconformity
	Cap Mountain	Lion Mountain sandstone
		Cap Mountain limestone
	Hickory	Hickory sandstone
		Unconformity
Pre-Cambrian basement rocks		

The Hickory sandstone was deposited on an irregular surface and within this area probably ranges between 50 and 200 feet in thickness. It is predominantly a brown sandstone with a thin zone of red friable sandstone at the top. Hickory sandstone is the predominant Paleozoic formation above the Smoothingiron granite. The density of the Hickory sandstone, as determined on five samples, ranges from 2.26 to 2.51 and averages 2.38.

The Hickory sandstone grades upward into the brown Cap Mountain limestone which in turn grades upward into the green glauconitic Lion Mountain sandstone. There is a sharp contact between the Lion Mountain sandstone and the overlying brown Welge sandstone. The Welge sandstone grades upward into Morgan Creek limestone, which is red at the base, grading upward into a gray limestone. The contacts between the Morgan Creek limestone, the greenish Point Peak shale, the white San Saba limestone, and the gray to pinkish gray Pedernales dolomite are fairly sharp. The Pedernales dolomite and the overlying unnamed dolomite of the Ellenburger formation are lithologically similar and are not separately mapped. In some areas of the Llano uplift the two dolomites are separated by a white limestone. Paleozoic rocks younger than the Hickory sandstone are chiefly situated north of the Valley Spring-Field Creek road, mostly north of the Smoothingiron granite mass, and another small area of these rocks situated just south of the granite border comprise Slick Mountain.

[6] Bridge, Josiah, and Barnes, V. E. *Stratigraphy of the Upper Cambrian, Llano uplift, Texas.* Manuscript.


LEGEND
Alluvium and Travertine
Cambro Ordovician dolomite
San Saba limest.
Point Peak shale
Morgan Creek ls.
Welge sandstone
Lion Mtn. sandst.
Cap Mtn. limestone
Hickory sandstone
Smoothingiron granite
Packsaddle schist and Valley Spring gneiss
Fault showing downthrow side
Strike and dip of metamorphic rocks
10°
Smooth-ingiron Mtn.
Cold
Creek
Baumann
Lone Mtn.
Cgr
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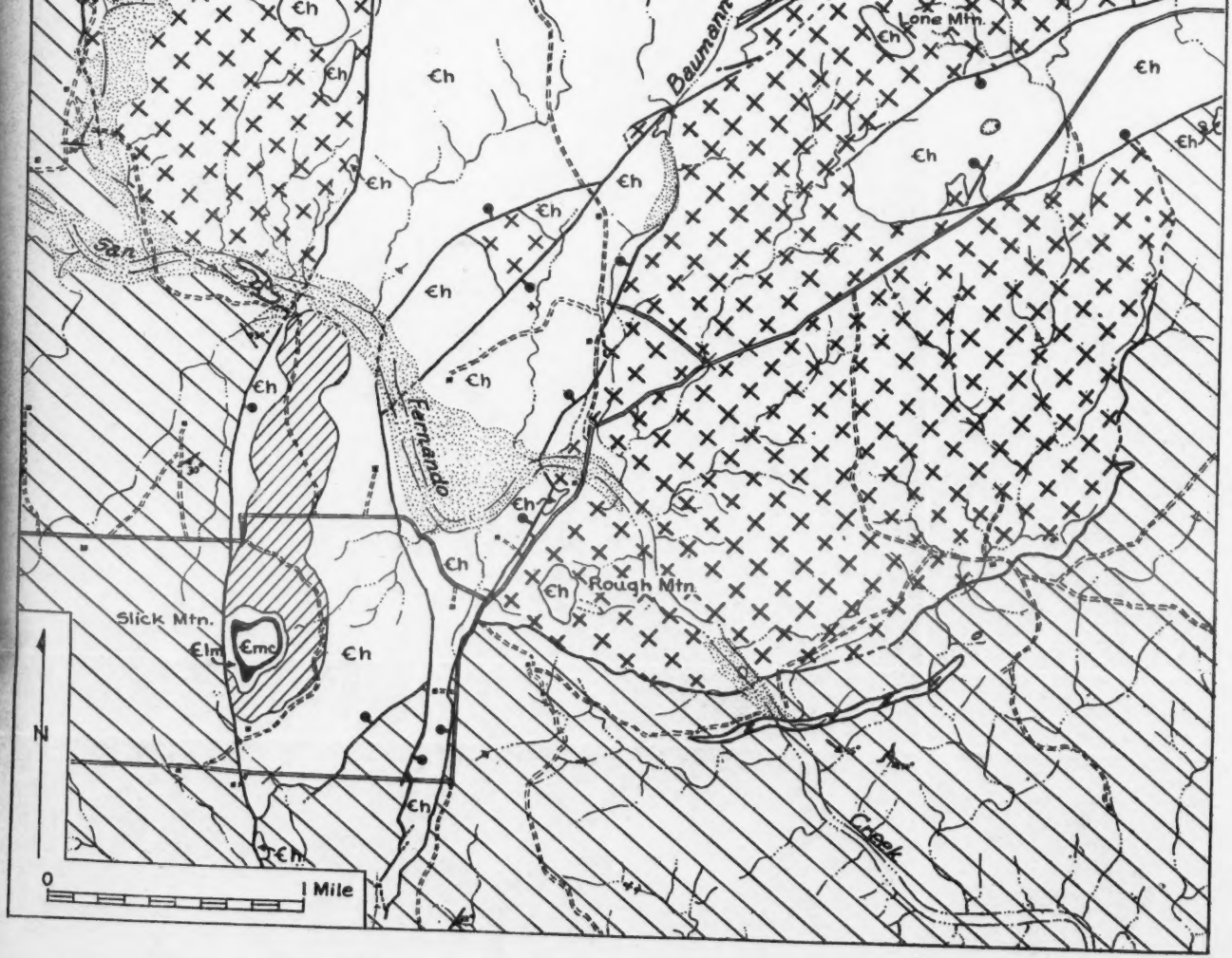

FIG. 7. Geologic map of the Smoothingiron granite mass, Llano County, Texas.

The Paleozoic rocks of the area have been highly faulted in a typical pattern indicating tensional forces acting in a definite direction. Fault directions throughout the Llano uplift are exemplified by those shown on the geologic map, Fig. 7. These faults predominantly trend northeast-southwest and north-south, with some trending east-west. In the Smoothingiron area the intersection of the north-south set of faults with a set trending roughly northeast-southwest produces a somewhat complicated pattern. Other faults of small throw are indicated on the aerial photographs, and were not placed on the map because of insufficient field evidence for their existence.

The gravity data indicate a slight influence caused by the north-south graben of Paleozoic rocks crossing the Smoothingiron granite mass. The otherwise smooth gravity contours circling the granite mass swing out slightly where they cross the graben, indicating, as they should, rocks of somewhat lower density. Another smaller graben having little if any effect upon the gravity data extends southwest from Valley Spring and dies out within the granite mass.

The pre-Cambrian rocks of the area older than the granite have been arbitrarily divided by Paige into the pink feldspathic Valley Spring gneiss and the basic dark colored Packsaddle schist, both originally of sedimentary origin. The Valley Spring gneiss is supposedly older than the Packsaddle schist, but from observations made about the Llano uplift it appears that there may be more than one zone of light colored rocks alternating with more than one zone of dark colored rocks. In the vicinity of the Smoothingiron granite mass various proportions of the two rock types may be found alternating in beds ranging from a few feet to many feet in thickness. The two rock types have not been separately mapped and indeed it is almost impossible to obtain sufficient data to do so. Exposures are limited largely to stream courses with large divide areas in which the soil cover is thick and little can be seen. The Valley Spring gneiss is more resistant to weathering than the Packsaddle schist; consequently, areas of outcrop of each cannot be used to estimate the relative abundance of the two rock types.

The Valley Spring gneiss of the area is composed mostly of a combination of minerals either albite and quartz, or microcline and quartz, or both albite and microcline and quartz. Other minerals which may be present mostly in small amounts are biotite, hornblende, muscovite, magnetite, and tremolite. The rocks containing appreciable amounts of tremolite such as those along San Fernando Creek to the

west of the granite mass are not strictly Valley Spring gneiss even though they are light colored and of similar density. Density determinations made on 25 different specimens of Valley Spring gneiss ranged from 2.60 to 2.67, with two exceptions, both of which were abnormal rocks. The average density of the Valley Spring gneiss is 2.64; which is only slightly higher than the density of the granite, which is 2.62.

The Packsaddle schist sampled in the Smoothingiron area consists mostly of hornblende, quartz, and oligoclase. Microcline is important in some samples, magnetite is usually present, and one sample contained about one percent of monazite, a rare earth phosphate. Densities of 8 samples of Packsaddle schist ranged from 2.91 to 2.99 and averaged 2.95. As pointed out above Valley Spring gneiss and Packsaddle schist are interlayered in various proportions throughout the area. So far as can be determined from outcrop data the area to the west of the Smoothingiron granite mass contains a lower percentage of Packsaddle schist than does the area to the east of the granite mass, and consequently will have a lower average density, but nevertheless an appreciably higher density than that of the granite.

MATHEMATICAL APPENDIX

The computations of gravitational force in this paper are based on an expression for the downward attraction at any point of a vertical cylinder whose upper boundary is a horizontal plane. The bottom of the cylinder is taken to be infinitely deep; the force of a finite cylinder is then computed from the difference between the attractions of two infinite cylinders whose tops are at different depths. The expression is not integrable for the general case, and is therefore used in several different forms for ease in evaluation. The simplest case (Eq. 1) is the well-known formula for the attraction at a point on the axis of the cylinder, where F is the force, s the anomalous density, k the gravitational constant, a the radius of the cylinder, and z the depth of its upper boundary.

$$F/ks = 2\pi(\sqrt{a^2 + z^2} - z). \tag{1}$$

The attraction at a point above the edge, if $z=0$, is given by Eq. 2,

$$F/ks = 4a \tag{2}$$

and, if $z \neq 0$, by Eq. 3,

$$F/ks + \pi z = (4a/c)\int_0^{\pi/2} \sqrt{1 - c^2 \sin^2\theta}\, d\theta. \qquad (3)$$

The right-hand member of Eq. 3 is the elliptic integral $E(c)$, where $c = 2a[4a^2+z^2]^{-1/2}$, and can be evaluated from tables. For other points in the plane of the top of the cylinder ($z=0$) there are two cases. If $b<a$ (b is the horizontal distance from axis to point of observation), the force is given by Eq. 4

$$F/ks = 4aE(b/a). \qquad (4)$$

If $b>a$, the force is given by Eq. 5.

$$F/ks = 4(a^2/b - b)K(a/b) + 4bE(a/b) \qquad (5)$$

where K is the complete elliptic integral $K(a/b)$.

Finally, attractions not in the plane of the top of the cylinder nor above its edge are most easily found by means of Nettleton's solid angle chart,[7] or by means of the expression

$$F/ks = 2\int_{-a}^{a} \sinh^{-1}\left\{(a^2 - x^2)^{1/2}[(b - x)^2 + z^2]^{-1/2}\right\} dx \qquad (6)$$

which can be evaluated approximately with little trouble.

DISCUSSION

Romberg and Barnes' paper suggests two lines of comment. (1) The evaluation of the gravity data suggests strongly, even though it does not prove, that the body of the Smoothingiron granite mass widens downward and extends only to a small depth of not more than one mile. This is particularly of interest in connection with Stenzel's study of the Wolf Mountain granite body[1] which appears to be a sheet of granite intruded along the contact zone of gneiss and schist pinched into the axes of the folds in the last stages of deformation, a "phacolith." It is to be hoped that a similar detailed study of the flow lines in the granite and of the structure of the surrounding metamorphic rocks will be made of the Smoothingiron mass for comparison with the gravity data. The writer suspects that the evidence will show the granite to occupy the cupola-like bulge of a minor anticline (or perhaps even a flat minor basin) superimposed on the major gneiss anticline that runs from Pontotoc southeast to beyond Oxford.

Into this picture of relatively thin granite sheets involved in the folding, the Midway sill, northwest of Burnet, fits very well. According to Stenzel[2] this sill follows the

[7] Nettleton, L. L. *Gravity and magnetic calculations*, GEOPHYSICS, Vol. VII, p. 303, July, 1942.

[1] H. B. Stenzel, *Structural study of a phacolith*, XVI Intern. Geol. Congr., 1933, Report, vol. I, 1936, pp. 361–367.

[2] H. B. Stenzel, *Pre-Cambrian structural conditions in the Llano region*, Univ. Texas Bull. 3401, 1934, pp. 74–79.

gneiss-schist boundary in strike and dip along its whole exposed length of three and a quarter miles. It is about a quarter of a mile thick. The numerous pegmatite dikes that cut it at right angles to the flow lines indicate that the granite was in the last stage of crystallization when it became involved in the folding.

Cumulative evidence thus is casting doubt on the interpretation of these granite masses as stocks with essentially vertical walls as which they were shown, for instance, diagrammatically in Keppel's recent paper.[3]

(2) For the ultimate vindication of the method of analysis employed in this case it is essential that it be applied to other bodies of intrusives with approximately circular groundplan especially such as may be expected to have the shape of vertical cylinders. Among granitic bodies, the most promising are those that cut across thick, folded, unmetamorphosed sediments. A fine example is the granite of the Sierra de Sarnoso[4] that lies athwart the folds of the thick Lower Cretaceous limestones of the Sierra de Mapimi in northeastern Durango, about twenty miles northwest of Torreon. An unusually well-mapped example is the granite area west of Falmouth in southern Cornwall.[5] In the latter case the attitude of the contact is well known at many points through the extensive copper and tin developments of the region which lie concentrated along the granite border. Here also large-scale topographic maps furnish adequate data for terrain corrections and the total relief is small (highest points between 700 and 819 feet above sea-level). In the Sierra de Sarnoso, on the other hand, the elevations range from 4000 to well over 5000 feet above sea-level and vertical airphotos are required to provide topographic control. But fortunately in our day neither topographic nor political obstacles are prohibitive any longer.

Perhaps even more inviting objects of study are found among the basic intrusives. There is, for instance, the norite mass near Peekskill, New York, where the flow lines are arranged in the shape of double funnels.[6] In the broadly oval body of basic rock of Magnet Cove, Arkansas,[7] the distribution of rock facies and belts of enclosed bed rock suggest upwelling of the magma in the center and a downward movement along the sides.

A successful gravimetric analysis of the Magnet Cove body would furnish an excellent basis for a systematic study of the hidden bodies of basic rock in Arkansas and elsewhere which were first recognized by the abnormally high magnetic anomalies associated with them. Examples in Arkansas are: the famous one at Rison, Cleveland Co., where the writer understands peridotite was struck by the drill at a depth of around

[3] David Keppel, *Concentric patterns in the granites of the Llano-Burnet region*, Texas, Geol. Soc. America, Bull., vol. 51, 1940, pp. 971–1000.

[4] L. B. Kellum, *Geology of the mountains west of the Laguna District*, Geol. Soc. America, Bull., vol. 47, 1936, pp. 1083–1084, and pl. 14.

[5] J. B. Hill and D. A. MacAlister, *The Geology of Falmouth and Truro*, Mem. Geol. Survey England and Wales, 1906, and Sheet 352 of the geological map.

[6] Robert Balk, *Die primäre Struktur des Noritmassivs von Peekskill am Hudson, nördlich von New York*, Neues Jahrb. Min., Beil. Bd. 57, 1927, pp. 249–303. For other references see S. J. Shand, *Phase petrology in the Cortlandt Complex, New York*, Geol. Soc. America, Bull., vol. 53, 1942, pp. 409–428.

[7] H. S. Washington, *Igneous complex of Magnet Cove, Arkansas*, Geol. Soc. America, Bull., vol. 11, 1900, pp. 389–416. For other references and comment on the interpretation of movement, see reference (10) below.

3600 ft., and the magnetic high about four miles southwest of Arkansas Post, where syenite was reported struck by the drill at a depth of about 4700 ft.

At points remote from the oil fields it is customary to ascribe abnormally high gravity and magnetic anomalies to rock bodies that are part of the pre-Cambrian basement. An interesting case was recently reported by Woollard[8] from the vicinity of Clay Center, Kansas. On the basis of a few stations along the line of his transcontinental section, Woollard has attempted to compute the dimensions of an assumed "gabbro" body in the crystalline basement, using the equations for a horizontal cylinder. But close to the line of his traverse, about fifteen miles east of Clay Center, weathered peridotite lies exposed and was reached in a shallow drill hole.[9] Once the effectiveness of the gravimetric analysis of simple bodies has been demonstrated this area offers a fine opportunity for the study of the relation between such isolated peridotite "plugs" and the broader areas of high positive gravity and magnetic anomalies with which they are associated. To the writer few problems in plutonic geology seem to be of greater importance to an understanding of the larger aspects of crustal deformation than the ascent of basic magma far from orogenic belts.

A last group of features that seems somehow connected with this rise of basic magma comprises the "cryptovolcanic" structures, of which the Serpent Mound structure of Southern Ohio and the Wells Creek Basin structure are the best known and most accessible examples.[10] A detailed gravimetric study may well settle definitely the question of their origin.

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[8] G. P. Woollard, *Transcontinental gravitational and magnetic profile of North America and its relation to geologic structure*, Geol. Soc. America, Bull., vol. 54, 1943, pp. 783–784. Reviewed by L. L. Nettleton in GEOPHYSICS, vol. VIII, No. 4, p. 419 (1943).

[9] R. C. Moore and W. P. Haynes, *An outcrop of basic igneous rock in Kansas*, Bull. Am. Assoc. Petrol. Geol., vol. 4, 1920, pp. 183–187.

[10] Walter H. Bucher, *Cryptovolcanic structures in the United States*, XVI Intern. Geol. Congr., 1933, Report, vol. 2, 1936, pp. 1055–1084.

THE PERIODIC VARIATIONS OF THE GRAVITATIONAL FORCE. I.*

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ABSTRACT

The expression for the variation of the gravitational field, at a particular place on the earth's surface, due to a tide producing body is put into a form which does not neglect terms or factors which will produce changes in the gravitational field of as much as 0.001 milligal. A method of carrying out routine calculations by means of a series of graphs is described.

INTRODUCTION

August Schmidt[1] at the beginning of this century described a trifilar gravity meter. Schweydar[2] fourteen years later refined Schmidt's instrument to such an extent that he was able to show that a variation of the gravitational field with a period corresponding to that demanded by theory existed. R. C. Hartsough,[3] during the years 1920–30, investigated this phenomenon with a short period gravity meter. Most of his results have never been published. Tomascheck and Schaffernicht[4] in 1932 published the results of extended, very carefully carried out experiments on this subject. Within the last ten years, Truman,[5] Wolf[6] and Wyckoff[7] have carried out measurements with commercial gravity meters. Adler,[8] Lambert[9] and Elkins[10] have,

* Presented at the Annual Meeting, Fort Worth, Texas, April, 1943.

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The work in connection with this paper was made possible by a grant from the University Research Institute.

[1] August Schmidt, *Das Trifilargravimeter*. Gerland Beitr. z. Geophys. *4*, 109–115, 1900.

[2] W. Schweydar, *Beobachtung der Aenderung der intensität der Schwerkraft durch den Mond*. Sita.-Ber. der Preuss. Akad. d. Wiss., Math.-phys. Kl., *14*, 454–465, Berlin, 1914.

[3] R. C. Hartsough, *Effect of Lunar Gravity upon a Quartz Thread Balance*. Phys. Rev., *19*, 282, 1922.

[4] Tomaschek and Schaffernicht, *The Temporal Variations in the Force of Gravity*. Ann. der Phys., *XV*, 787, 1932.

[5] O. H. Truman, *Variations of Gravity at One Place*. Astrophysical J., *89*, 445–464, 1939.

[6] Alfred Wolf, *Tidal Force Observations*. GEOPHYSICS, *6*, 1, 81–83; *5*, 4, 317–320.

[7] R. D. Wyckoff, *Study of Earth Tides by Gravitational Measurements*. Trans. Am. Geophysical Union, 1936, 46–42.

[8] J. L. Adler, *Simplification of Tidal Corrections for Gravity Meter Surveys*. GEOPHYSICS, *7*, 1, 35–44.

[9] Walter D. Lambert, *Notes on Earth Tides*. GEOPHYSICS, *8*, 1, 51–56.

during the last two years, contributed papers to this Journal on computing methods. Lambert[11] has prepared a report on Earth Tides which gives an excellent overall picture of the present status of our knowledge of the tides in the solid earth and the observed gravitational variations associated therewith.

The work of the above investigators has shed considerable light on the gravitational variations at certain locations. They all show

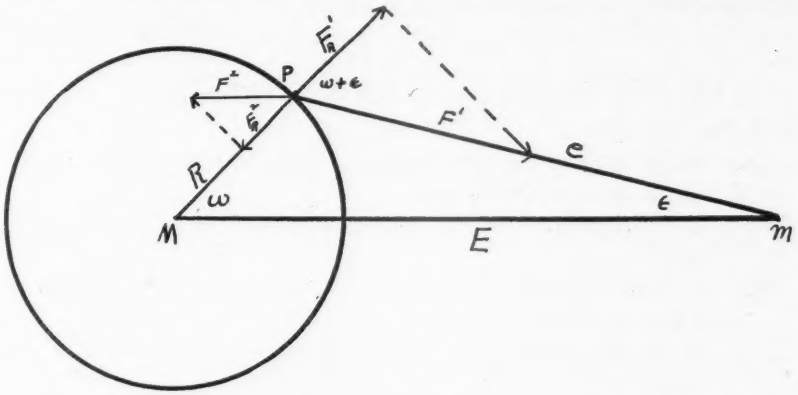


FIG. 1. Illustration of the significance of the notation used.

that the changes in the gravitational field are larger than the changes in field due to the sun and moon alone. The magnitude of the difference between the observed variations and those calculated as direct effect of the sun and moon, however, vary widely in the various places. Most of the observations have not extended over a sufficiently long time to show whether the magnitude of this difference varies at a particular station. The phase relations between the tide producing forces and the observed gravitational field are even more inconsistent.

This unsatisfactory status of the problem is sufficient excuse from a purely academic viewpoint to attempt further precision measurements. The exploration geophysicist is not warranted in refining his gravity meter technique beyond present practice until he has better information regarding the periodic change of the gravitational field.

Two years ago Drs. Romberg and LaCoste placed at the disposal of the Physics Department of the University of Texas one of their

[10] T. A. Elkins, *Nomograms for Computing Tidal Gravity*. GEOPHYSICS, *8*, 2, 134–145.

[11] Walter D. Lambert, *Report on Earth Tides, 1936–1938*. U. S. Coast and Geodetic Survey, Special Publication No. 223.

commercial gravity meters. This instrument was made self recording in a manner to be described in a later paper, and has now been operating, with only minor interruptions, since the summer of 1942. The data thus gathered are being compared with the gravitational forces exerted by the sun and moon alone. The results of these measurements will be presented to this Journal at a later date for publication. The present paper concerns itself only with the method of calculating the tide producing forces due to sun and moon.

THEORY

In Fig. 1 the large circle is the surface of the earth, the observer being at the point P.

m is the mass of the tide producing body (moon or sun),
M is the mass of the earth,
e is the distance of the tide producing body m to the observer at P,
E is the distance from the center of the earth to the center of the tide producing body,
ω is the geocentric angle, between observer, center of earth and tidal body,
ϵ is the angle between observer, tidal body, and the center of the earth,
F^1 is the Newtonian field at the observer due to m,
F^2 is the centrifugal reaction due to the center of the earth moving in an orbit around the common center of mass of the earth and tidal body. (Note that the observer moves in an orbit of the same shape and size as that traveled by the earth's center and therefore has the same centrifugal reaction.)
γ is the universal gravitational constant,
F_R^1 is the radial or vertical component of F^1,
F_R^2 is the radial or vertical component of F^2,

$$F^1 = \gamma m/e^2 \qquad \text{and} \qquad F^2 = \gamma m/E^2;$$

$$F_R^1 = (\gamma m/e^2)\cos(\omega + \epsilon) \quad \text{and} \quad F_R^2 = (\gamma m/E^2)\cos\omega.$$

ΔG is the difference of these two vertical components, and, therefore:

$$\Delta G = ym[(1/E^2)\cos\omega - (1/e^2)\cos(\omega + \epsilon)] \qquad (1)$$

where a positive value of ΔG is directed inward to the earth's center. This expression is rigorous for the tidal field due to an external body

m. However, in order to calculate ΔG for any instant, the values of ω, E, ϵ and e for the body concerned must be known. It is because of the laborious process involved in getting all of these quantities that the above expression for ΔG is modified.

By making use of the relation $e \sin \epsilon = R \sin \omega$, expanding $\cos(\omega+\epsilon)$, and the law of cosines, Eq. 1 becomes

$$\Delta G = (\gamma m/E^2)[\cos \omega - (\cos \omega - R/E)\{1 - 2(R/E) \cos \omega + R^2/E^2\}^{-3/2}].$$

If this expression is expanded according to the binomial theorem

$$\Delta G = (\gamma m/E^2)(R/E)[1 - (3/2)(R^2/E^2) - (3 - 15R^2/E^2) \cos^2 \omega - 17.5(R^2/E^2) \cos^4 \omega + (4.5 \cos \omega - 7.5 \cos^3 \omega)R/E]. \quad (2)$$

Here terms within the bracket involving R/E to a higher degree than the second have been neglected.

For the moon R/E has the mean value of about 1/60 so that the $\cos \omega$ and $\cos^3 \omega$ terms may contribute as much as 0.04 to the value of the bracketed expression, whose total value is about 2 when ω is 0 or π. Neglect of these terms would give an error of the order of 2 per cent. The $\cos^4 \omega$ term can contribute as much as 0.0048, which for some types of work cannot be neglected.

Inserting numerical values for R^2/E^2, and since

$$G = \gamma M/R^2$$

where G is the gravitational field due to the earth's mass at the observing point P,

$$\Delta G = (Gm/M)(R/E)^3[0.9996 - 2.9959 \cos^2 \omega - 0.0048 \cos^4 \omega + (4.5 \cos \omega - 7.5 \cos^3 \omega)R/E].$$

R in the above expression is the distance from the observing point to the center of the earth. The *Almanac*[1] gives the equatorial horizontal parallax p. If R_e is the equatorial radius, then $R = CR_e$ for a particular latitude. Therefore,

$$(R/E)^3 = (CR_e/E)^3 = C^3 \tan^3 p,$$

where

$$C^2 = [1 - (2b^2 - b^4) \sin^2 \phi]/(1 - b^2 \sin^2 \phi), \quad (3)$$

in which b is defined from

$$(R/R_e)^2 = 1 - b^2.$$

[1] *The American Ephemeris and Nautical Almanac.*

R_p is the pole distance to the center of the earth. ϕ is the latitude of the observer. At Austin, Texas, the value of C is 0.99915. Strictly $R=CR_e+h$ where h is the distance of the observer above sea level. Except for elevations of several miles, h can be neglected. Finally,

$$\Delta G = (GC^3\, m/M)\, \tan^3 p[0.9996 - 2.9959 \cos^2 \omega - 0.0048 \cos^4 \omega + (4.5 \cos \omega - 7.5 \cos^3 \omega)C \tan p]. \quad (4)^*$$

The factor

$$(GC^3 m/M)$$

is a constant for a particular point of observation and within a few

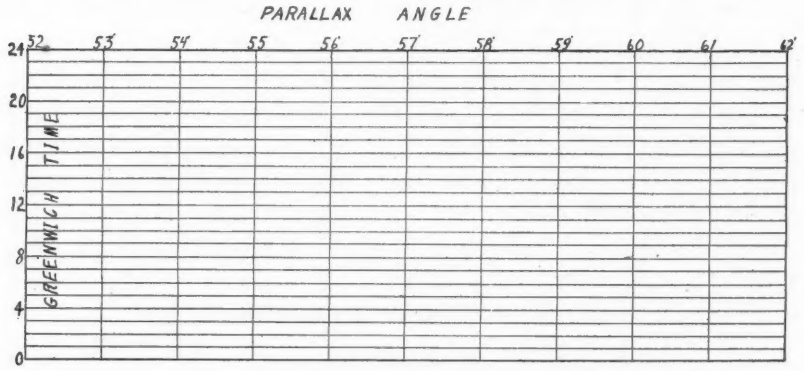


FIG. 2 is for the purpose of interpolating the Moon's parallax angle. In the working chart this figure is drawn to such a scale that each hour in time is 1 cm on the ordinate and each minute in parallax angle is 6 cm on the abscissas.

tenths of a per cent the same for all places on the earth. p and cos ω are the varables to be used in calculating ΔG.

The American Ephemeris and Nautical Almanac gives p for Greenwich Midnight and Noon. By means of a straight edge and Fig. 2, linear interpolations can be made for each hour of the day. In the actual chart used for this purpose, centimeter coordinate paper is used and the scale is such that one centimeter on the ordinate is 1 hour in time and each minute in parallax angle is 6 cm. on the abscissas. To illustrate its use, for January 1, 1942, the Ephemeris

* Tan p is theoretically incorrect, and should be replaced by sin p, although this change will leave the numerical values unchanged.

The value of m/M for the moon which was used in the calculations is 0.01228, taken from the *Handbook of Chemistry and Physics*, 24th Edition.

gives for Greenwich Midnight 54′ 14.69″ and for Greenwich Noon of the same day 54′ 21.58″. A sraight edge is placed on the chart so that it passes through positions $y=0$, $x=54'\ 14.69''$ and $y=12$, $x=54'\ 21.58''$. The value of p can then be read off at each hour from

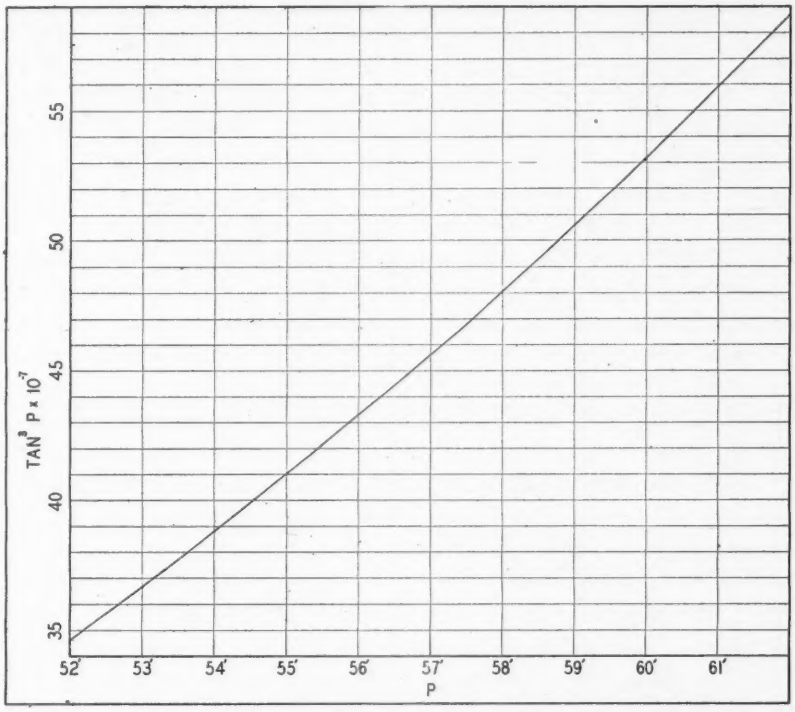


FIG. 3. Chart for determination of $\tan^3 p$. Having the parallax angle p, the value of $\tan^3 p$ can be read from this graph.

0 to 12. The same procedure is repeated for Greenwich hours 12 and 24. $\text{Tan}^3\ p$ can then be read from a chart such as Fig. 3.

Cos ω is given by

$$\cos\omega = \sin\delta \sin\phi + \cos\delta \cos\phi \cos H$$

where δ is the declination, H is the local hour angle and ϕ is the local latitude. This equation can be plotted for a particular latitude as a family of straight lines where cos ω is the ordinate and sin δ sin ϕ the y intercept for a particular δ, cos H is the abscissa and cos δ cos ϕ the slope for a particular δ.

A family of such straight lines for δ's from 25° to −25° for each 5° is shown in the chart of Fig. 4. In actual practice only that portion of the chart lying in the first and fourth quadrant was drawn since the third and second quadrant can be obtained by rotating the

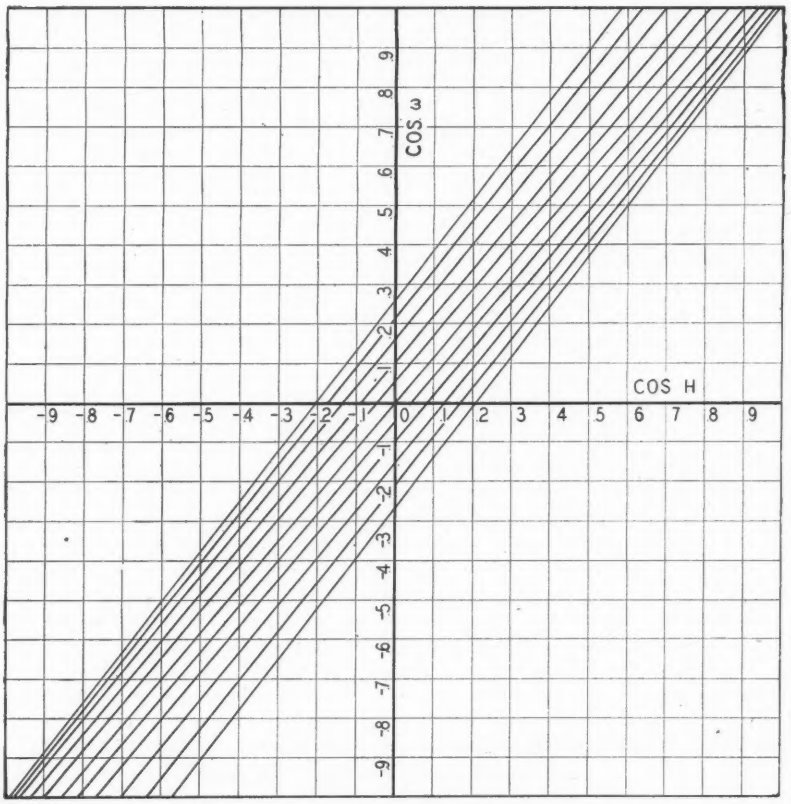


FIG. 4. The equation $\cos\omega = \sin\phi \sin\delta + \cos\phi \cos H \cos\delta$ is here plotted using $\cos\omega$ as ordinate and $\cos H$ as abscissas. ϕ, the local latitude is constant, and δ, the declination angle, is a parameter for each straight line. In the working graph a line is drawn for each degree of declination from −28° to +28°.

figure through 180°. The working chart is drawn to a scale such that for $\cos H = 1$ and $\cos\omega = 1$, each cover 100 cm. Also a line is drawn for each integer degree value of δ from −28° to +28°. H and δ are obtained in the usual manner from the *Almanac*.

The value of the bracketed factor in Eq. 4 can be plotted as a family of curves against cos ω, tan p being a parameter for each curve. Since the variation of p does not greatly influence the value of the factor in brackets it is sufficient to draw four curves, one for the maximum value of p and one for the minimum value of p for cos ω positive and another pair for maximum and minimum p for cos ω negative.

The procedure for calculating ΔG for the moon is as follows:

First, for each hour of the day, Greenwich time, the hour angle H is obtained. This is corrected for local time. If the *American Ephemeris and Nautical Almanac* is used, H is calculated by subtracting Right Ascension from Sidereal Time and then subtracting the difference between Greenwich Time and Local Time. The H so obtained is in hours, minutes and seconds. Since cos H is needed, it is convenient to make or obtain a cosine table in which the angles are given in hours, minutes and seconds, rather than in degrees, minutes and seconds. The *American Air Almanac* gives H for the moon directly in degrees, minutes and seconds and so by using the latter a subtraction is eliminated and ordinary cosine tables can be used. It is to be noted that H must still be corrected for local time. Declination δ can be obtained from either almanac directly. Having δ and cos H, cos ω is read from the chart in Fig. 4. p is obtained for midnight, noon and midnight from the *Almanac*, and by linear interpolation with use of the chart in Fig. 2, p for each hour is obtained. Tan^3 p is then read from the chart in Fig. 3. Having p and cos ω, the value in brackets in Eq. 4 times (GC^3m/M) is read from the chart in Fig. 5. Finally the value read from Fig. 5 is multiplied by tan^3 p for the time in question to give ΔG.

For the sun the expression for ΔG (Eq. 2) can be shortened to

$$\Delta G = GC^3(m_s/M)\overline{(R_e/E)}^3D^{-3}[1 - 3\cos^2\omega] \qquad (5)^*$$

in which $\overline{R_e/E}$ is the mean value of R_e/E for the sun. This is about 0.000046, so that the term in the brackets of Eq. 2 which involves R/E as a factor is entirely negligible compared with $[1-3\cos^2\omega]$. The mean value R_e/E was introduced along with the relative radius vector of the sun since the latter is more convenient to use than the sun's parallax angle.

* A value of 329,390 for m_s/M, taken from the *Handbook of Chemistry and Physics*, 24th Edition, was used in the calculations. $\overline{R_e/E}$ was taken from the *American Ephemeris* value of 8.80 seconds of arc for the mean solar parallax.

To obtain H for the sun the local mean time is corrected by the equation of time obtained from the *Almanac*. δ for the sun is given

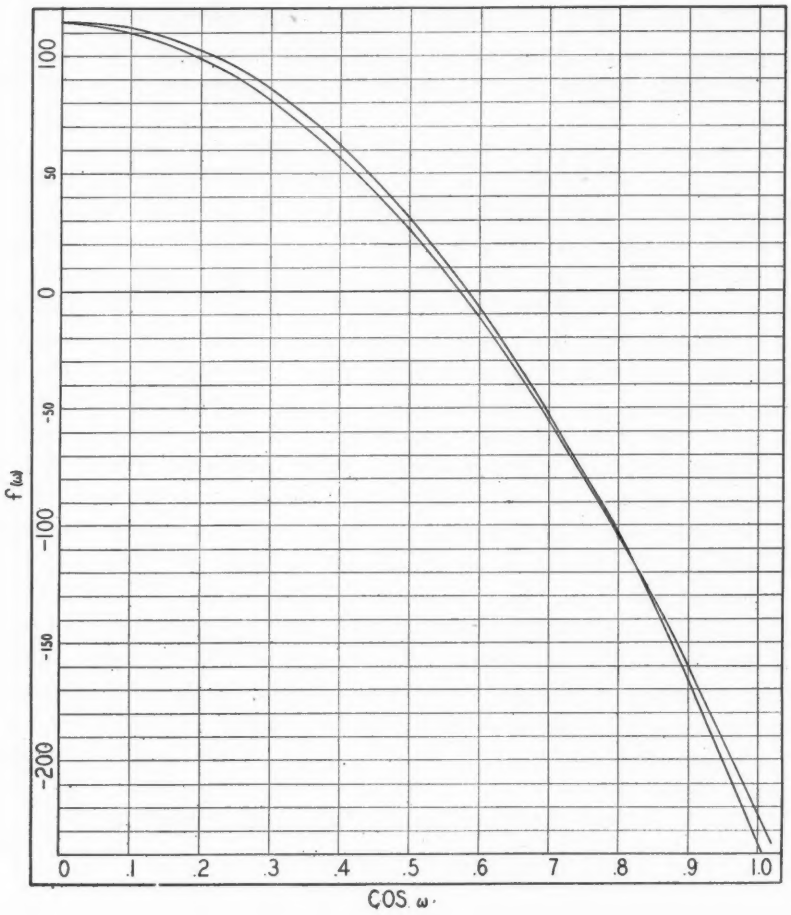


FIG. 5. Given $\cos\omega$ and p, the value of the function $f(\omega)=GC^3(m/M)[0.9996-2.9959\cos^2\omega-0.0048\cos^4\omega+(4.5\cos\omega-7.5\cos^3\omega)\,C\tan p]$ can be read from this chart. In practice, four curves are drawn instead of two, namely, for $+\cos\omega$ and $p=52'$, $+\cos\omega$ and $p=62'$, $-\cos\omega$ and $p=52'$, and $-\cos\omega$ and $p=62'$.

only for Greenwich midnight so that a chart, such as Fig. 6, is convenient for linear interpolation for each hour of the day. For example, for January 1, 1942, the *Ephemeris* gives $-23°\ 4'\ 17.4''$ for the angle

of declination of the sun and $-22°\ 59'\ 29.6''$ for January 2, 1942. A straight edge is placed on Fig. 6, passing through coordinates $y=0$, $x=4'\ 17''$ and $y=24$, $x=59'\ 29''$. The minute and seconds value of δ can then be read off at each hour. The declination of the sun never changes by more than 90 minutes of arc a day so that Fig. 6 is ample for interpolation purposes. An alternate method which is very rapid

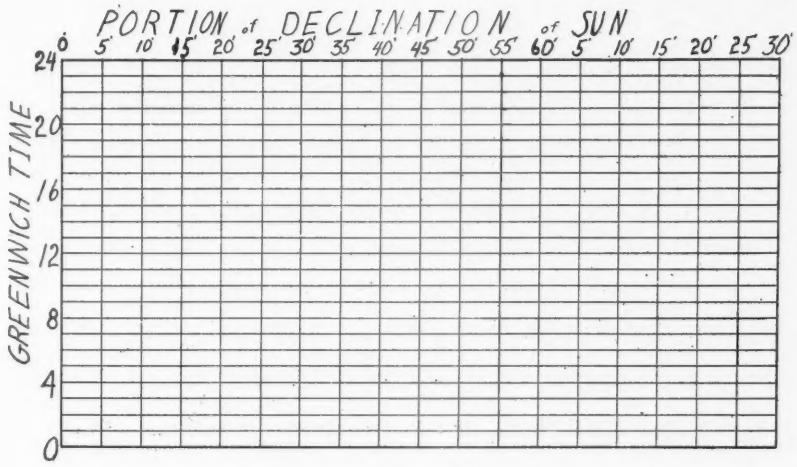


FIG. 6. Chart for interpolating the declination angle of the sun, having the values at time 0 and 24. The angle changes very slowly so that only the minutes part of the angle need be on the chart.

if a calculating machine is at hand, is to divide the change in δ for the day by 24 and add this value progressively from hour to hour to the value for δ at midnight. D, the radius vector for the sun, varies so little that it can be considered constant for one day. A chart, Fig. 8, will give D^3 as a function of D.

Fig. 7 is a chart in which

$$GC^3(m_s/M)(\overline{R_e/E})^3[1 - 3\cos^2\omega]$$

is plotted as a function of cos ω. Having obtained cos ω with the aid of Fig. 4, the above expression is read from Fig. 7 and this is then multiplied by $1/D^3$ to obtain ΔG for the sun. The ΔG for the sun plus ΔG for the moon then gives the variation in gravity to be expected were the earth rigid.

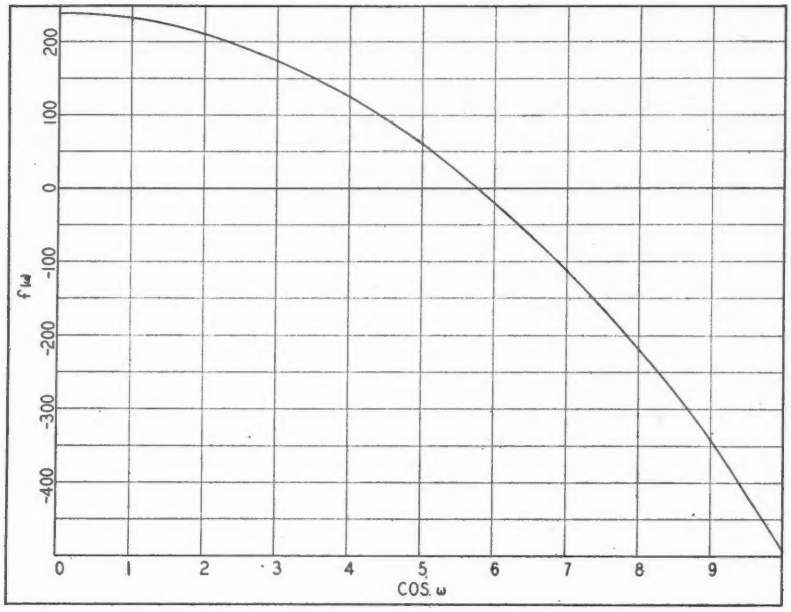


FIG. 7. $f(\omega) = GC^3(m_s/M)(\overline{R_e/E})^3[1-3\cos^2\omega]$ as a function of $\cos\omega$ for the sun.

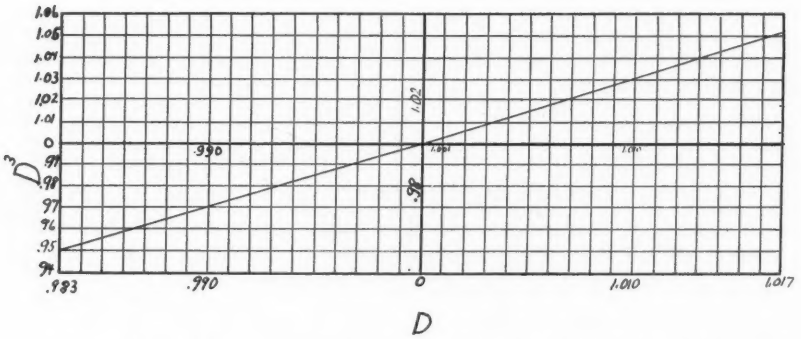


FIG. 8. Chart for computing D^3 as a function of the value of D, the radius vector from earth to sun, which is obtained from the *Almanac*.

CONCLUSION

During the last nine months calculations as outlined above have been made each day for each hour of the twenty-four in order to compare the computed results with the observations. Two students, each

putting in two and one-half hours a day, were able to make a day's calculations. This method of calculation does not neglect any factor or term which might affect the result by as much as 0.001 milligal.

For gravity meter survey work the time of calculation would be considerably less since one would only be interested in correcting for the eight or ten hours of operating time. Also, since in the field a gravity meter cannot be read to better than 0.01 milligal, the care used in reading charts, shown in Figs. 4, 5, 7, would not be so great, thus greatly speeding up the work.

In the near future the results of gravity meter observations of the variation of ΔG with time will be presented to this journal for publication.

PATENTS*

GEOCHEMICAL PROSPECTING

U. S. Re. 22,345. L. W. Blau. Iss. 7/13/43. App. 2/27/39 and 8/20/42. Assign. Standard Oil Development Co.

Process for Locating Valuable Subterranean Deposits. A method of soil analysis prospecting in which soil samples are examined for the presence of hydrocarbon consuming bacteria by the application of a color indicator.

U. S. No. 2,324,085. L. Horvitz and E. E. Rosaire. Iss. 7/13/43. App. 12/21/39. Assign. E. E. Rosaire.

Geochemical Well Logging. A method of geochemical well logging consisting of taking well samples over a considerable part of the hole, analysing them for significant hydrocarbon content and plotting concentration as a function of depth.

U. S. No. 2,324,107. S. J. G. Pirson. Iss. 7/13/43. App. 3/1/39. Assign. Geochemical Service Corp.

Method for the Geochemical Prospection of Hydrocarbon Deposits. A method of soil analysis prospecting in which all samples are taken from depths having the same acidity, and correcting the analyses for moisture content, degree of subdivision, and depth from which the sample was taken.

U. S. No. 2,325,057. H. Hoover, Jr. and H. E. Metcalf. Iss. 7/27/43. App. 5/28/40. Assign. Consolidated Engineering Corp.

Means for Obtaining Soil Samples. A soil sampler which, after cutting a hole having a soil projection on the bottom, inverts a tin can over it and cuts off the projection and seals it in the tin can until ready to be analysed.

U. S. No. 2,328,555. H. Hoover, Jr. Iss. 9/7/43. App. 5/27/40. Assign. Consolidated Engineering Corp.

Well Logging Method. A method of hydrocarbon well logging by analysing drilling mud for light and heavy hydrocarbons and in which a correction is made for hydrocarbon concentration in the mud prior to its entering the circulation cycle.

U. S. No. 2,330,716. L. Horvitz. Iss. 9/28/43. App. 11/24/39. Assign. E. E. Rosaire.

Geochemical Prospecting. A method of soil analysis prospecting in which samples are treated either with heat or acid so as to disintegrate or dissolve carbonates and thus release any significant constituent and subsequently analyzing for this constituent.

U. S. No. 2,330,717. L. Horvitz. Iss. 9/28/43. App. 12/9/40. Assign. E. E. Rosaire.

Geochemical Prospecting. A method of analysing soil samples for significant constituents in which interstitial air and loosely held gases are pumped off and discarded, and a more vigorous degassing treatment is subsequently used to evolve gases which are analysed for significant constituents.

* Abstracts by O. F. Ritzmann, Gulf Research & Development Co.

U. S. No. 2,330,758. M. S. Taggart, Jr. Iss. 9/28/43. App. 12/26/40. Assign. Standard Oil Development Co.

Geochemical Prospecting. A method of treating soil samples or soil in situ by first soaking with an aqueous solution which will give off a gas when subsequently treated with a strong mineral acid and analysing the evolved gas.

U. S. No. 2,329,824. J. G. Campbell. Iss. 9/21/43. App. 12/31/40. Assign. Ralph H. Fash.

Method of Determining Suitable Areas for Oil Exploration. A method of localizing areas for more intensive exploration by observing the intensity of fluorescence of water samples taken from streams and wells.

U. S. No. 2,330,021. M. A. Arthur. Iss. 9/21/43. App. 11/25/40. Assign. Standard Oil Development Co.

Geochemical Prospecting. A method of geochemical prospecting in which soil samples are dried and ground to a uniform size and analysed for selected constituents in the arc of an emission spectrograph.

U. S. No. 2,330,026. L. W. Blau. Iss. 9/21/43. App. 11/25/40. Assign. Standard Oil Development Co.

Geochemical Prospecting. Extracting soil samples with a liquid capable of extracting some product of the action of any contained hydrocarbon-consuming bacteria on hydrocarbons and measuring the light absorption power of the extract in the region of 4600 to 6000 Angstroms.

GRAVIMETRIC PROSPECTING

U. S. No. 2,325,005. D. H. Clewell. Iss. 7/20/43. App. 6/21/41. Assign. Socony-Vacuum Oil Co., Inc.

Gravity Meter. A gravity meter whose suspended element is of such a shape and density that changes in gravity forces due to elevation changes are compensated by changes in the buoyant effect of the air.

U. S. No. 2,327,692. L. L. Antes. Iss. 8/24/43. App. 4/7/42. Assign. Standard Oil Development Co.

Gravity Meter. A temperature compensated horizontal torsion spring gravimeter having an auxiliary mass mounted on a bimetallic strip.

U. S. No. 2,327,697. F. G. Boucher. Iss. 8/24/43. App. 2/7/41. Assign. Standard Oil Development Co.

Gravity Meter. A horizontal torsion spring gravimeter having a symmetrically shaped mass to avoid barometric errors and having increased sensitivity by using a spring at right angles to the torsion spring and fastened to a point on the mass beyond its axis.

SEISMOGRAPH PROSPECTING

U. S. No. 2,324,816. W. T. Born. Iss. 7/20/43. App. 5/26/33 and 8/19/42. Assign. Geophysical Research Corp.

Seismic Surveying. A seismograph amplifier circuit permitting shot moment to be

put on a detector trace and having a condenser discharge type of expander initiated by the first arrival.

U. S. No. 2,325,199. J. P. Woods. Iss. 7/27/43. App. 6/30/41. Assign. Shell Development Co.

Method and Apparatus for Seismic Exploration. A simple seismograph detector readily adaptable for multiple use, which consists of a permanent magnet elastically suspended near an armature, the detector cable itself being laced through the magnetic circuit to serve as a single turn pickup coil.

U. S. No. 2,326,153. W. H. Mayne. Iss. 8/10/43. App. 3/13/40. Assign. Olive S. Petty.

Seismic Circuit. A circuit for obtaining seismograph shot moment from the break of the cap bridge wire by using a rectifying tube and filter condenser.

U. S. No. 2,326,696. R. N. Stoddard. Iss. 8/10/43. App. 4/30/40. Assign. Westinghouse Electric & Manufacturing Co.

Blasting Machine. A blasting machine having a rectifier connected between the generator and a condenser and a discharge tube between the condenser and the caps, so that discharge does not occur until sufficient energy to fire all the caps has been stored in the condenser.

U. S. No. 2,328,222. M. D. McCarty. Iss. 8/31/43. App. 10/1/41. Assign. Socony-Vacuum Oil Co., Inc.

Geophone. A balanced armature reluctance type geophone having a low reluctance magnetic connection between like poles of the upper and lower magnets.

U. S. No. 2,329,558. S. A. Scherbatskoy. Iss. 9/14/43. App. 9/7/37. Assign. Engineering Laboratories, Inc.

Automatic Volume Control. An AVC circuit for seismograph amplifiers in which the a-c signal is shunted by two rectifiers connected in opposite directions and controlled by the signal amplitude.

U. S. No. 2,329,570. R. Wellenstein, W. Holle and M. Schumacher. Iss. 9/14/43. App. 3/27/39 and 4/4/40. Vested in Alien Property Custodian.

Device for Regulating the Sensitivity of Signal Receiving Apparatus. An AVC circuit for echo sounding amplifiers in which rectified signal is applied to the grid of an amplifier and also having an expander circuit controlled by the device which initiates the sound impulse.

U. S. No. 2,329,721. H. Hoover, Jr., C. J. Morgan and N. J. Christie. Iss. 9/21/43. App. 9/30/38. Assign. Consolidated Engineering Corp.

Geophysical Exploration System. A system of seismograph shooting which provides continuous control with offset detectors close to the shot point and one common trace on each record to provide overlap.

U. S. No. 2,330,216. H. Hoover, Jr. and M. Swan. Iss. 9/28/43. App. 1/30/39. Assign. Consolidated Engineering Corp.

Apparatus for Seismic Prospecting. A method of controlling the frequency response

of a seismograph amplifier as a function of time by changing the d-c magnetization of the core material in the filter chokes in such a way that the induced drift is balanced out.

WELL LOGGING AND SURVEYING

U. S. No. 2,323,484. J. Neufeld. Iss. 7/6/43. App. 5/12/41. Assign. Well Surveys, Inc.

Well Logging Method and Apparatus. A gamma ray well logging method which uses as an exciting source a material in which artificial radioactivity has previously been induced.

U. S. No. 2,324,103. L. C. Miller. Iss. 7/13/43. App. 12/19/40. Assign. Eastman Oil Well Survey Corp.

Well Survey Apparatus. A well surveying instrument having a double container the inside one being thermally insulated from the outer one but in contact with a cooling unit.

U. S. No. 2,324,682. R. DeLong. Iss. 7/20/43. App. 3/26/41. Assign. Forty per cent to Fohs Oil Co.

Side Wall Coring Tool. A device for mechanically cutting a core from the side wall of a hole by means of a fluid motor driven core barrel.

U. S. No. 2,324,698. M. L. Hart. Iss. 7/20/43. App. 9/21/40. Assign. Halliburton Oil Well Cementing Co.

Well Measuring Device. A device for locating the position of a plug in a well by means of a weight on the end of a wire line, the line passing over a pulley mounted so as to give an electrical signal when sudden variations in line tension occur.

U. S. No. 2,324,814. H. C. Beene, H. Marks and D. L. Mitchell. Iss. 7/20/43. App. 9/3/40.

Test Device for Oil Wells. A device having two packers and arranged so that fluid entering between them may be pumped to the surface.

U. S. No. 2,326,219. J. T. Hayward. Iss. 8/10/43. App. 12/30/39.

Well Depth Recording. A device for recording depth of hole drilled by means of a drive connected to the crown block pulley, the drive operating through a differential gearing so that maximum downward position of the drill is held on a depth record and negative movements are held on an off-bottom record which may be corrected manually for new drill sections added.

U. S. No. 2,326,405. L. Spencer. Iss. 8/10/43. App. 6/2/41. Assign. Lane-Wells Co.

Side Wall Sampling Device for Well Bores. A cable operated side wall sampler having an electric motor which by means of a rack successively engages a series of sampling tubes on gear segments and forces them into the wall.

U. S. No. 2,326,640. R. F. Davis. Iss. 8/10/43. App. 1/29/41. Assign. Well Surveys, Inc.

Apparatus for Determining the Dip in the Earth's Substrata. A method of determining the direction and average amount of dip by means of a single current electrode lowered

into the well and three Y-connected current electrodes on the surface, and having an indicator connected to three potential electrodes on the surface.

U. S. No. 2,327,023. H. S. Danner. Iss. 8/17/43. App. 12/23/41.

Side Wall Drilling and Sampling Tool. A device for cutting a core from the side wall of a hole at an acute upward angle, the cutter being driven by an electric motor which also drives a pump for hydraulically operating a clamping shoe and a mechanism for withdrawing the completed core.

U. S. No. 2,327,768. L. C. Miller. Iss. 8/24/43. App. 12/12/39. Assign. Eastman Oil Well Survey Corp.

Method of and Means for Orienting Tools in Well Bores. Determining the orientation of a whipstock with respect to the low side of a slant hole by fixing a magnet to the stock and running a wire line surveying instrument which indicates a plumb-bob vertical and is aligned by the magnet.

U. S. No. 2,329,732. F. M. Varney and J. A. Varney. Iss. 9/21/43. App. 9/8/41.

Signaling Deviation Detector. A pendulum clinometer which may be run inside the drill pipe, the pendulum being freed when mud circulation is stopped and emitting signals to indicate the inclination by means of obstruction pressure release waves when mud circulation is resumed.

U. S. No. 2,330,394. R. W. Stuart. Iss. 9/28/43. App. 7/25/40. Assign. Stanolind Oil and Gas Co.

Detection of Salt in Drilling Fluids. A temperature compensated electrical conductivity measuring device using two conductivity cells in temperature equilibrium, one cell containing the sample and the other cell containing a standard mud or electrolyte.

U. S. No. 2,330,752. S. T. Sikes, Jr. Iss. 9/28/43. App. 11/24/41. Assign. Standard Oil Development Co.

Rate-of-Penetration Indicator. A drilling rate recorder in which the chart moves in proportion to the increase in depth and a recording clock draws a transverse line whose peak is proportional to the time required to drill unit distance, the clock being restarted at the beginning of each unit.

U. S. No. 2,330,753. S. T. Sikes, Jr. Iss. 9/28/43. App. 11/24/41. Assign. Standard Oil Development Co.

Direct Reading Rate-of-Penetration Meter. A drilling rate recorder in which the chart moves in proportion to the increase in depth and a recording millivoltmeter records the emf of a generator connected to the shaft of a drilling line sheave.

MISCELLANEOUS

U. S. No. 2,323,556. E. O. Mattocks. Iss. 7/6/43. App. 11/29/40. Assign. Phillips Petroleum Co.

Method and Apparatus for Determining Effective Porosity. Determining the porosity of a core sample by placing it in a closed container, applying dry gas under pressure and measuring the volume expansion required to restore atmospheric pressure.

U. S. No. 2,324,102. L. C. Miller and R. F. Bolton. Iss. 7/13/43. App. 2/9/40. Assign Eastman Oil Well Survey Co.

Means for Directional Drilling. An asymmetrical drill bit which may also be used as a spudder and which has nozzles through which a chemical may be pumped to disintegrate the formation in a chosen direction.

U. S. No. 2,324,160. J. E. Hoffoss. Iss. 7/13/43. App. 7/3/42. Assign. Reed Roller Bit Co.

Core Taking Apparatus. A wire line coring device which allows drilling fluid to pass around it and which is engaged with the drill bit by the fluid pressure.

U. S. No. 2,324,174. A. L. Rodgers. Iss. 7/13/43. App. 5/3/40. Assign. One-half to Two States Drilling Co.

Weight Indicator. A spring and pointer type weight indicator which is inserted in a split in the supporting cable.

U. S. No. 2,324,254. T. A. Bertness, N. Johnston and D. O. Newton. Iss. 7/13/43. App. 3/11/41. Assign. Socony-Vacuum Oil Co., Inc.

Method of Removing Mud Barriers from Oil Wells. Removing the mud barrier from the sides of a well by the application of either non-aqueous, water absorbing liquids, hot dry crude oil or a highly concentrated calcium chloride brine.

U. S. No. 2,324,340. C. P. Walker and E. E. Simmons. Iss. 7/13/43. App. 2/8/41. Assign. C. P. Walker.

Detector for Pressure Wave Translation Systems. A hot wire microphone biased with a steady flow of air so that it will distinguish condensations and rarefactions.

U. S. No. 2,324,956. B. W. Sewell. Iss. 7/20/43. App. 11/25/40. Assign. Standard Oil Development Co.

Borehole Tool. A tool for cutting vertical slots in the sides of a hole by means of an endless chain on an expanding parallelogram driven by the drill stem and forced nto the formation by fluid pressure.

U. S. No. 2,325,218. V. J. Beissinger. Iss. 7/27/43. App. 8/11/41. Assign. Richfield Oil. Co.

Process for the Gravel Packing of Wells. A method of gravel packing a well by feeding gravel with a gelatinous binder into the annular space between the casing and a working string while rotating the latter, then removing the working string and draining the gelatinous binder.

U. S. No. 2,326,114. A. J. Zschokke. Iss. 8/10/43. App. 12/8/41. Assign. Lane-Wells Co.

Gun Perforator. A gun perforator in which the igniter simultaneously discharges three shots 120° apart in order to minimize gun recoil and splitting of well casing.

U. S. No. 2,326,406. L. Spencer. Iss. 8/10/43. App. 8/18/42. Assign. Lane-Wells Co.

Gun Perforator. A small diameter sand line operated perforating gun having oblique

cartridge chambers, the uppermost shot being set off by a go-devil and each shot setting off the succeeding one by means of an interconnecting firing pin.

U. S. No. 2,326,577. J. U. Teague and G. E. Cannon. Iss. 8/10/43. App. 9/27/39 and 1/1/43. Assign. Standard Oil Development Co.

Removal of Mud Cake in Casing Cement Jobs. The addition of sand or abrasive particles to the cement so as to cut the mud cake by abrasion and obtain a good bond between the cement and the formation.

U. S. No. 2,327,017. L. C. Chamberlain. Iss. 10/17/43. App. 3/15/37. Assign. The Dow Chemical Co.

Treatment of Wells Producing Mineral Fluid. A method of increasing oil production through removal of connate water by treating the formation with a non-acid water soluble liquid, such as alcohol, having a lower surface tension than water.

U. S. No. 2,327,051. O. W. Lyons and J. H. Adkinson. Iss. 8/17/43. App. 7/27/40. Assign. The Dow Chemical Co.

Apparatus for Treating Wells. An acidizing gun run on tubing and having nozzles through which acid may be forced under pressure, and also having a valve operated by setting the gun on bottom to open ports so that the acid may be returned to the gun tubing by applying pressure to the annular space.

U. S. No. 2,327,111. G. O. Kimmel. Iss. 8/17/43. App. 7/27/40.

Apparatus for Removing Samples from Flowing Streams. A sampling device for the well head of distillate wells which uses a sharp edged sampling nozzle and having the velocity of flow into the nozzle controlled to be proportional to the velocity of the main stream.

U. S. No. 2,327,118. J. D. MacKnight. Iss. 8/17/43. App. 12/28/40. Assign. The Texas Co.

Submersible Barge. A barge for drilling and pumping operations in water locations having a base plate and supporting structure which may be lowered below the bottom of the barge to rest on the water bottom.

U. S. No. 2,327,141. L. Spencer. Iss. 8/17/43. App. 9/23/42. Assign. Lane-Wells Co.

Gun Perforator. A perforating gun in which the detonator is placed between the projectile and the powder charge, and each shot is fired by the concussion of the previous shot transmitted through the well fluid.

U. S. No. 2,327,340. L. E. Couch. Iss. 8/24/43. App. 12/9/40. Assign. Well Tool Development Corp.

Perforating Gun for Oil Well Casings. A perforating gun having a cage whose frictional drag on the sides of the hole operates a safety, the gun being fired by a time clock which is started simultaneously with removal of the safety by slightly raising the gun in the well.

U. S. No. 2,327,362. J. S. McDonald and W. E. A. Ruska. Iss. 8/24/43. App. 10/5/40. Assign. Well Tool Development Corp.

Improvement in Well Tools. A perforating gun having a safety slide operated by friction on the sides of the hole but which may be locked and later released by a go-devil and an electric timer to successively fire the shots provided the safety slide is in the proper position.

U. S. No. 2,327,501. T. S. Chapman. Iss. 8/24/43. App. 12/5/40. Assign. Standard Oil Development Co.

Drilling Fluid. A salt water drilling mud containing a tanning agent and a protein or salts of proteins to reduce loss of water into porous formations.

U. S. No. 2,327,539. E. D. McAlister. Iss. 8/24/43. App. 12/3/40. Assign. Standard Oil Development Co.

Apparatus for Gas Analysis. A method of analysing hydrocarbon gases by infrared absorption measurements, the wave length band entering the absorption cell being selected by successively reflecting the light from mirrors which reflect only energy in the absorption band.

U. S. No. 2,327,642. W. L. Horner. Iss. 8/24/43. App. 1/3/38. and 8/8/40. Assign. Core Laboratories, Inc.

Method and Apparatus for Measuring Porosity of Solids. A calibrated plunger pump and pressure chamber which may be used to measure the volume of a core sample and the volume of pore space by measuring the amount of mercury forced into the pores at high pressure.

U. S. No. 2,327,659. L. C. Miller. Iss. 8/24/43. App. 6/1/40. Assign. Eastman Oil Well Surveying Corp.

Reading Instrument. A reading device for a magnetically oriented well surveying instrument dial, which magnetically reorients the dial and is graduated so that the azimuth of a mark indicating maximum deviation from the vertical can be read.

U. S. No. 2,328,001. D. H. Furse and L. J. Neuman. Iss. 8/31/43. App. 3/11/40.

Means and Method of Bringing Oil Wells into Production. A method of gun perforating in which the perforator is lowered on the end of the flow string and is set off by a go-devil and the gun shots and vibrations incident to oil flow into the pipe are detected and recorded by a seismic system at the surface.

U. S. No. 2,328,309. G. F. Turechek and L. Spencer. Iss. 8/31/43. App. 9/19/42. Assign. Lane-Wells Co.

Firing Head for Gun Perforator. A firing head for explosively operated well tools which is tripped by a go-devil sliding on the supporting cable and having a friction operated safety which permits firing only when the tool has last been moved downward.

U. S. No. 2,329,157. M. W. Frank. Iss. 9/7/43. App. 4/30/41. Assign. The Dow Chemical Co.

Well Treating Tool. An acidizing tool for applying high velocity streams of acid to the formation, the nozzles of the device being protected by an acid soluble cover to prevent entrance of foreign material while the tool is being lowered to position.

U. S. No. 2,329,225. L. L. Snyder and A. Hollander. Iss. 9/14/43. App. 12/3/40. Assign. Byron Jackson Co.

Coring Device. A wire line core barrel having at its upper end a Venturi passage and a conduit connecting the Venturi throat to the top of the core barrel so as to draw the core into the core barrel.

U. S. No. 2,329,405. R. S. Mann. Iss. 9/14/43. App. 6/27/40.

Core Drill. A drill for continuously cutting core and having at its lower end core cut-off jaws operated either by compressed air or an explosive charge.

U. S. No. 2,329,810-11-12. T. Zuschlag. Iss. 9/21/43. App. 10/18/41, 11/6/41, 12/5/41, respectively. Assign. Magnetic Analysis Corp.

Electromagntic Inspection. Apparatus for a-c inspection of metallic material to locate flaws by passing it through coils connected to two oscillators and tuned detector circuits.

U. S. No. 2,329,878. B. Cerf. Iss. 9/21/43. App. 3/14/41. Assign. Graphite Frecs Co.

Drilling Fluid and the Method of Drilling and Lubricating Wells. Adding graphitic carbon or domestic amorphous graphite to drilling mud to impart lubricating qualities.

U. S. No. 2,330,083. B. W. Sewell. Iss. 9/21/43. App. 3/3/42. Assign. Standard Oil Development Co.

Retractable Drill Bit. A drill bit which may be run on a wire line and which locks on to the bottom of the drill pipe and is released by upward pull on the wire line.

U. S. No. 2,330,110. R. C. Buchan. Iss. 9/21/43. App. 10/31/41. Assign. Standard Oil Development Co.

Method of Placing Explosives in Shooting Wells. A method of tamping a well shot with material which may subsequently be dissolved out by a reagent such as acid.

U. S. No. 2,330,145. H. A. Reimers. Iss. 9/21/43. App. 8/2/40. Assign. The Dow Chemical Co.

Method of Sealing Pores in Subterranean Formations Contiguous to Deep Well Bores. A method of sealing off undesired water or oil horizons by pumping in a mixture of sodium silicate and sulphuric acid.

U. S. No. 2,330,157. J. C. Stokes. Iss. 9/21/43. App. 8/1/42. Assign. Reed Roller Bit Co.

Wire Line Core Barrel. A drilling bit having movable cutting arms which are held out to cut a core when a core barrel is lowered on a wire line, the arms moving in to simply cut hole when the core barrel is removed.

U. S. No. 2,330,336. W. J. Crites. Iss. 9/28/43. App. 12/9/40. Assign. Phillips Petroleum Co.

Apparatus for Pumping Fluids. An electric motor driven positive displacement rotary pump preceded by a centrifuge so that abrasive matter is removed from the fluid before it enters the pump.

U. S. No. 2,330,432. F. N. Fossati. Iss. 9/28/43. App. 2/6/42. Assign. Standard Oil Co. of California.

Weight Indicator. A weight indicator in which the sensitive element is held against abutments on a load carrying yoke by a spring so that excessive loads cannot injure the sensitive element.

U. S. No. 2,330,509. O. J. McCullough. Iss. 9/28/43. App. 4/30/40. Assign. McCullough Tool Co.

Gun Tester. A combined gun perforator, packer and sampler to be carried on the drill pipe and operated by it.

U. S. No. 2,330,564. C. C. Dyer. Iss. 9/28/43. App. 5/12/41.

Mud Ejection Control. A dissolvable flow bean which constricts the opening in the drill stem sufficiently to prevent mud from being ejected from the top of the drill pipe while it is being lowered into the hole.

U. S. No. 2,330,721. M. C. Leverett. Iss. 9/28/43. App. 5/18/42. Assign. Standard Oil Development Co.

Method of Determining Connate Water Content of Cores. Placing a core sample in capillary contact with water under a pressure differential comparable with that between the water table and the connate water originally in the sample and analysing the sample after equilibrium has been established.

PUBLICATIONS RECEIVED

(The publications listed below were received since issuance of GEOPHYSICS for October, 1943, and are available for loan to the membership. Articles cited are those of particular interest to geophysicists.)

American Journal of Science, Vol. 237 (1939); Vol. 241 (1943), Nos. 4 (April); 6 (June)' "Causes of Variations in Radioactivity Data," by N. B. Keevil, A. R. Keevil' W. N. Ingham, and G. P. Crombie; 9 (September); 10 (October); 11 (November), "Helium Indexes for Several Minerals and Rocks," by N. B. Keevil (New Haven).,

Bulletin of the American Association of Petroleum Geologists, Vol. 27, Nos. 9–11 (September–November, 1943, Tulsa).

Economic Geology Vol. XXXVIII, Nos. 3 (May), 6 (September–October), 7 (November, 1943, Lancaster).

Geophysical Abstracts (United States Department of the Interior), Nos. 87 (July–December, 1936); 93, 94 (April–September, 1938); 96, 97 (January–June, 1939); 99 (October–December, 1939); 101 (April–June, 1940); 103–111 (October, 1940–December, 1942, Washington).

Independent Petroleum Association of America Monthly, The, Vol. XIV, Nos. 5–8 (September–December, 1943, Tulsa).

Journal of Applied Physics, Vol. 14, No. 8, Special Issue on the Mobilization of Scientific Resources (August); 9–11 (September-November, 1943, Lancaster).

Journal of the Institute of Petroleum, Vol. 29, Nos. 236, 237 (August, September, 1943, London).

Petroleum, Vol. VI, Nos. 7, 9–11 (July, September–November, 1943, London).

Proceedings of the Cambridge Philosophical Society, Vol. 38, Nos. 2, 3, 4 (April, July, November, 1942, Cambridge).

Review of Scientific Instruments, The, Vol. 14, Nos. 8–11 (August–November, 1943, Lancaster).

Publicaciones del Instituto de Fisiografia y Geologia, No. XIV, "*Antigüedad Geológica del Yacimiento de los Restos Humanos de la 'Gruta de Candonga' (Córdoba)*," by Alfredo Castellanos (Rosario, Argentina, 1943).

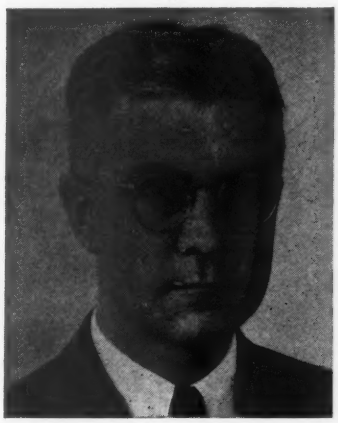
Terrestrial Magnetism and Atmospheric Electricity, Vol. 41 (1936), Nos. 1 (March), "Geomagnetic Coordinates for the Entire Earth," by A. G. McNish; 2 (June), "Maximum Sensitivity-Setting of the Dip-Needle," by James Fisher and Jerry H. Service; "The Space-Gradients of the Earth's Magnetic Field," by S. Chapman; 3 (September), "Application of Alternating-Current Methods of Detection to Earth-Inductors for Marine and Land Observations," by E. A. Johnson; 4 (December); Vol. 42 (1937), Nos. 1 (March), "Short-Time Magnetic Fluctuations of Local Character " by Victor Vacquier; 2 (June); 3 (September) "Electromagnetic Method for Testing Rock-Samples," by A. G. McNish; 4 (December), "An Improved Inductor-Compass," by Ross Gunn; Vol. 43 (1938), Nos. 1 (March), "A Method for Producing Non-Magnetic Castings of Copper , Brass, and Aluminum," by W. F. Steiner; 2 (June), "Natural Residual Magnetism of Eruptive Rocks," by J. G. Koenigsberger; "An Electromagnetic Method of Determining Induction-Coefficients of Magnetometer-Magnets," by J. H. Nelson; 3 (September), "Natural Residual Magnetism of Eruptive Rocks, Part II," by J. G. Koenigsberger; 4 (December), "An Alternating-Current Apparatus for Measuring Small Magnetic Moments," by E. A. Johnson and A. G. McNish; "Magnetization of Unmetamorphosed Varves and Marine Sediments," by A. G. McNish and E. A. Johnson; Vol. 44 (1939), Nos. 1 (March), "A Primary Standard for Measuring the Earth's Magnetic Vector: I—Theory," by E. A. Johnson; 2–4 (June–December); Vol. 45 (1940); Vol. 46 (1941), Nos. 1 (March), "On the Analysis of Surface Magnetic Fields by Integrals, Part I," by E. H. Vestine; 2–4 (June–December); Vol. 47 (1942); Vol. 48, Nos. 1 (March), 3 (September), (Cincinnati).

World Petroleum, Vol. 14, Nos. 10–13 (September-December, 1943, New York).

CONTRIBUTORS

DART WANTLAND received the B.S. degree in C.E. from Colorado College in 1921, and the M.S. degree in Geophysics from the Colorado School of Mines in 1926. He was employed in geological and geophysical work by the Midwest Refining Company from 1925 to 1929. Mr. Wantland has been associated with the Geophysical Department of the Colorado School of Mines since 1929 as an instructor and assistant professor, with consulting work in geophysical prospecting for petroleum and minerals during the summer. Mr. Wantland is licensed by the State of Colorado as a geophysical engineer, and holds memberships in the Society of Exploration Geophysicists (regional editor 1942–); the American Association of Petroleum Geologists, and the Seismological Society of America.

DART WANTLAND



R. W. LAWRENCE

ROBERT W. LAWRENCE received his B.S. degree in chemical engineering in 1924 at the University of California, and his Ph.D. degree in physical chemistry in 1929 from the same university, where he was a student of Dr. G. N. Lewis. He had a teaching fellowship there for three years. Dr. Lawrence's association with Hercules Powder Company began soon after he received his Ph.D. degree when he became a research chemist at the Experiment Station, Kenvil, New Jersey. He is now the Assistant Leader of the Explosives Group at the Hercules Experiment Station, Wilmington, Delaware, where he is engaged in a number of investigations on explosives and related subjects, especially in studies on the mechanism of detonation of explosives. He has made extensive studies on powder used in seismographic prospecting. Dr. Lawrence is a member of the American Chemical Society, the American Association for the Advancement of Science and the Sigma Xi and Phi Lambda Upsilon honorary fraternities.

T. R. SHUGART

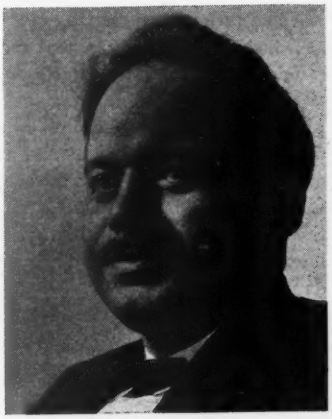
T. R. SHUGART received his B.S. degree from Texas Christian University in 1933. He spent one year as a graduate student in the Department of Physics at Duke University, after which he was employed by Geophysical Service, Inc., in 1934 and 1935. He continued his studies in Physics at California Institute of Technology in 1935 and 1936. Since 1936 he has been employed by The Geotechnical Corporation as seismograph party chief and supervisor. He is a member of the American Physical Society, the Society of Exploration Geophysicists, the American Association for the Advancement of Science and the American Association of Petroleum Geologists.

STANLEY W. WILCOX received his B.A. from the University of Minnesota in 1927 znd his M.S. in 1933. He was employed by the Geophysical Research Corporation from 1928 to 1930 as observer and computer. During 1932 he was an engineer with Roseau County, Minnesota, Highway Department, and from 1934 to 1936 geophysical engineer for the Minnesota State Highway Commission. Since 1936 he has been employed with the Seismograph Service Corporation.

He is a member of the Society of Exploration Geophysicists, American Association of Petroleum Geologists, American Institute of Mining and Metallurgical Engineers, and Sigma Xi. He is the first geophysicist to be registered with a state board as a geophysical engineer.

STANLEY W. WILCOX

ARTHUR E. LOCKENVITZ received his B.S. degree from Illinois Wesleyan University in 1925, and his M.A. degree from Indiana University in 1926. The following year he was in the development division of the Western Electric Company in Chicago. The academic year of 1927–28 he spent at the Universities of Goettingen and Hamburg. Since the fall of 1928 he has been a member of the Physics Department of the University of Texas. He is a member of Sigma Xi and of The American Physical Society.



A. E. LOCKENVITZ

Photographs and biographies of contributors to this issue not appearing above have been published previously, as follows: ALFRED WOLF, Vol. VII., No. 4, p. 428 (October, 1942); L. L. NETTLETON, Vol. VII., No. 3, p. 329 (July, 1942); T. A. ELKINS, Vol. VII., No. 1, p. 101 (January, 1942); FREDERICK ROMBERG, Vol. VI, No. 4, p. 461 (October, 1941); VIRGIL E. BARNES, Vol. VIII, No. 1, p. 72 (January, 1943).

THE SOCIETY ROUND TABLE

ANNOUNCEMENT OF 1944 ANNUAL MEETING

The 14th annual meeting of the Society of Exploration Geophysicists will be held at Dallas, Texas, March 21 and 22, with headquarters in the Baker Hotel. The American Association of Petroleum Geologists will convene on March 22–23, and the Society of Economic Paleontologists and Mineralogists will also meet on the latter day. On March 21, the annual business meeting will be held, and officers elected for 1944–45 will be announced. Morning and afternoon technical sessions will follow the business meeting, and at 8:00 P.M. in the evening the annual meeting of the A. A. P. G. Research Committee will be held. On March 22 the annual joint meeting of the three organizations will be held, featuring the presidential addresses and other papers of general interest. Topics of general interest are also scheduled for discussion on the following day.

Cecil H. Green, of Geophysical Service, Inc., 1311 Republic Bank Bldg., Dallas, Texas, has been appointed Chairman of the Program and Arrangements Committee. Serving with him in the Houston-Dallas-Ft. Worth Area will be E. D. Alcock, National Geophysical Co., Tower Petroleum Bldg,, Dallas, and John H. Wilson, Independent Exploration Co., Ft. Worth National Bank Bldg., Ft. Worth Texas. Other members of the Committee are as noted:

Atlantic Coast Area—L. L. Nettleton, Gulf Research and Development Co., P.O. Box 2038, Pittsburgh, Pennsylvania

Pacific Coast Area—Raymond A. Peterson, United Geophysical Co., 1255 East Green St., Pasadena, California

Rocky Mountain Area—Dart Wantland, Colorado School of Mines, Golden, Colorado

Tulsa Area—Norman Ricker, Carter Oil Co., P.O. Box 801, Tulsa, Oklahoma

The principal source of papers for the Society Journal, GEOPHYSICS, is, of course, the annual meeting. Members are accordingly urged to prepare papers for presentation at the technical sessions, or to be read by title if they cannot be delivered in person. Those members planning to present papers should get in touch with their District Program and Arrangements Committee member at once, in order that time may be scheduled.

No organized entertainment is planned. In view of limited hotel facilities, members should not plan to bring their wives. Further, members should not plan to attend unless they have been assured of hotel accommodations. Those planning to attend should write or wire at once regarding space.

The ballot reprinted below was mailed to all active members of the Society of Exploration Geophysicists on December 15, 1943. Active members who failed to receive ballots may secure them by notifying J. F. Gallie, Business Manager, P. O. Box 1925, Washington, D. C. *Only active members who have paid 1944 dues are eligible to vote.*

OFFICIAL BALLOT

FOR THE YEAR APRIL, 1944—APRIL, 1945

For the Election of Officers for the

SOCIETY OF EXPLORATION GEOPHYSICISTS

Before voting, please note the following extracts from the Society Constitution:
Article V-A—Officers

1. **The officers of the Society shall be a President, a Vice-President, a Secretary-Treasurer, and an Editor. These, together with the Past President, shall constitute the Executive Committee and managers of the Society. Officers shall be elected for a term of one year with the exception of the Editor, who shall be elected for a term of three years.***

2. **. . . Each member shall cast one vote for each officer to be elected and shall return his ballot to the Secretary-Treasurer. Ballots to be valid must be enclosed in an envelope carrying on the outside the written signature of the member submitting the ballot, and must be received by the Secretary-Treasurer at his officially recognized address not later than ten days prior to the Annual Meeting. Only ballots received from Members in good standing as of a date ten days prior to the Annual Meeting shall be valid. . . .**

FOR PRESIDENT

W. M. RUST, JR.	☐
C. B. BAZZONI	☐
.....	☐

FOR VICE-PRESIDENT

ROLAND F. BEERS	☐
HENRY C. CORTES	☐
.....	☐

FOR SECRETARY-TREASURER

W. HARLAN TAYLOR	☐
DART WANTLAND	☐
.....	☐

* Joseph A. Sharpe elected Editor 1942-1945.

After voting, place in accompanying official envelope, which should then be signed and mailed to the

SECRETARY-TREASURER
HART BROWN
P. O. Box 6005
Houston, Texas

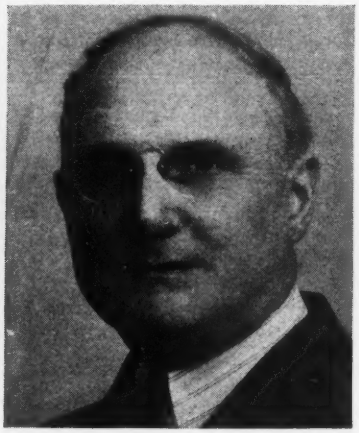
NOMINEES FOR 1944–1945 EXECUTIVE COMMITTEE

The following brief biographical sketches are presented in an attempt to acquaint members with nominees appearing on the official ballot which was mailed out December 15, 1943.

FOR PRESIDENT

W. M. RUST, JR., received his A.B. in 1928 from Rice Institute and served as a fellow there from 1928 until 1931, in which year he received his Ph.D. in Mathematics and Geophysics. He served as a Mathematics Instructor at Rice Institute 1931–1932; International exchange fellow in Germany 1932–1933; and Instructor and tutor in mathematics at Harvard University 1933–1934. In 1934 he joined the staff of the Geophysics Research Division of the Humble Oil and Refining Company as a Research

W. M. RUST, JR.



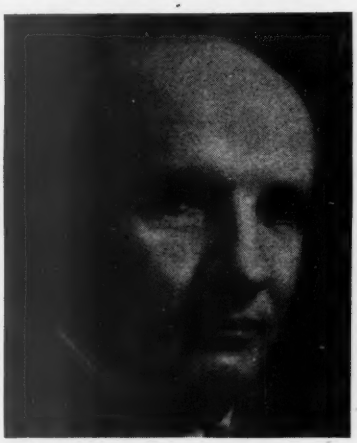
C. B. BAZZONI

Geophysicist, engaging in research on seismograph prospecting and electrical well-logging including the design of various electronic and mechanical equipment. He continued in this capacity until February, 1938, when he was made Division Head. He is a member of the American Mathematical Society, the American Physical Society, the American Geophysical Union, the American Association for the Advancement of Science, the American Institute of Mining and Metallurgical Engineers, the Seismological Society of America, and the Society of Exploration Geophysicists, of which he was Secretary-Treasurer in 1941–1942 and Vice-President in 1943–1944.

C. B. BAZZONI received his B.A., M. A., and in 1914, his Ph.D., from the University of Pennsylvania. From 1915 until 1917, when he joined the American Expeditionary Force, he worked with Sir O. W. Richardson at the University of London as Harrison Research Fellow. For the following two years he served with the A.E.F. in France as Captain of Engineers, in field command of the American Sound Ranging Service. In connection with this work he received the Military Cross from the British, the Order Officier d'Academie of the Institute of France from the French, and a Citation subsequently covered by the Order of the Purple Heart from the A.E.F. From 1919 until

1921 he served as Assistant Professor of Physics at the University of Pennsylvania and, for the following seventeen years, as Professor of Experimental Physics. While on leave of absence in 1925–1926, he organized the Geophysical Department of the Sun Oil Company, and has subsequently been in charge of it. In 1938 he resigned from the University and became Chief Geophysicist of Sun. From 1925 until 1940 he served as Major in the Field Artillery Reserve, in charge of the training of regular army officers in sound ranging while at the University. During the Second World War he has been a Sectional Member of the National Defense Research Committee's Division of Physics and a Regional Advisory Council Member of the Smaller War Plants Corporation. He is a member of the Science and Arts Committee of the Franklin Institute, and an Associate

ROLAND F. BEERS



HENRY C. CORTES

Editor of the Institute Journal; he is also a Fellow of the Physical Society and of the American Association for the Advancement of Science; and a member of the Optical Society, the Seismological Society, the Geophysical Union, the Society for X-ray and Electron Diffraction, and the Society of Exploration Geophysicists.

FOR VICE-PRESIDENT

ROLAND F. BEERS received the degree of E.E. in 1921 from Rensselaer Polytechnic Institute, Troy, New York. He remained at the Institute for one year as Instructor in Physics and Electrical Engineering, and then became Development Engineer in Western Electric's New York City Engineering Department. For two years thereafter he was Consulting Radio Engineer, publishing several articles on the development of a.c. power supply units for broadcast receivers. In 1925 he became Research Engineer for Raytheon, and in 1927 was appointed Physicist for the Submarine Signal Corporation of Boston. In 1928 he received the degree of S.M. in Electrical Engineering from the Massachusetts Institute of Technology, and at the end of that year joined the Geophysical Research Corporation in Houston as Party Chief. In 1931 he became Party Chief for Geophysical Service, Inc., and was made Vice-President of the company in 1934. In 1936 he organized the Geotechnical Corporation, of which he is now President. In 1940 he initiated graduate studies at Harvard University and

M. I. T. in the field of geology, and received his Ph.D. from the latter in May, 1943. His studies are now being continued at the Institute, where he is a staff member with the rank of Research Associate. He is the author of several papers pertaining to the reflection seismograph, and holds a number of patents in this field. He is a member of the American Geophysical Union, the Acoustical Society of America, the American Association of Petroleum Geologists, the American Institute of Mining and Metallurgical Engineers, the Seismological Society of America, the American Geographical Society, the American Association for the Advancement of Science, and the Society of Exploration Geophysicists, and is an associate of the Institute of Radio Engineers, the Franklin Institute, and the New York Academy of Sciences.

HENRY C. CORTES attended the University of the South, at Sewanee, Tennessee. In February, 1922, he entered the oil business, starting as a roughneck on a rotary drilling rig at the Hull Salt Dome Field, Liberty County, Texas. This experience further stimulated his interest in exploration geology, an interest in which he was very materially aided through acquaintance and friendship with Wallace E. Pratt, the late E. T. Dumble, Alexander Deussen, the late L. P. Garrett, Dilworth S. Hager, L. P. Teas, and others. In 1924 he was employed in the Vacuum Oil Company's Geological Department. Convinced that geophysics was to play a leading role in finding new fields, he became keenly interested in the early torsion balance and refraction seismograph work and interpretation. Soon after he was placed in charge of Vacuum's geophysical crews, consisting of torsion balance and refraction parties, Geophysical Research Corporation introduced the reflection seismograph; upon his recommendation, some of the earliest work of this nature was done for Vacuum. When the Magnolia Petroleum Company merged with Vacuum, with formation of the Socony-Vacuum Oil Company, he was placed in charge of Magnolia's geophysical exploration, in which capacity he is still employed. He has had a major role through geological and geophysical interpretation, in locating a number of oil and gas fields, among them Iowa, Cameron Meadows, Roanoke, Woodlawn, and West Gueydan in the Louisiana Gulf Coast, and Seeligson, LaGloria, and Tomball in the Texas Gulf Coast. He is a member of the American Association of Petroleum Geologists and Vice-Chairman (Geophysics) of the Association's Committee on Applications of Geology, Vice-President of the Dallas Petroleum Geologists, and a member of the Houston Geological Society, the Dallas Petroleum Club, and the Society of Exploration Geophysicists, in which he is serving as a member of the War Efforts Advisory Committee.

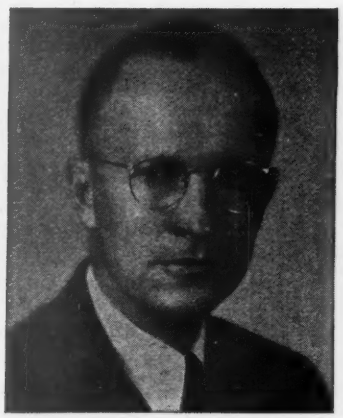
FOR SECRETARY-TREASURER

W. HARLAN TAYLOR received his B.S. in Geology in 1929 from Dartmouth College. Upon graduation, he joined the Geological Department of the Sinclair-Prairie Oil Company, doing field work in Kansas and Oklahoma. From 1930 until 1932 he did graduate work at Stanford University, receiving his M.S. in Geology. In 1933 he joined the staff of the Petty Geophysical Engineering Company. He is now District Supervisor in Petty's Houston Office. He is a member of the American Association of Petroleum Geologists, the Houston Geological Society, and the Society of Exploration Geophysicists.

DART WANTLAND received the B.S. degree in C.E. from Colorado College in 1921, and the M.S. degree in Geophysics from the Colorado School of Mines in 1926. He was employed in geological and geophysical work by the Midwest Refining Company from 1925 to 1929. Mr. Wantland has been associated with the Geophysical Department

of the Colorado School of Mines since 1929 as an instructor and assistant professor, with consulting work in geophysical prospecting for petroleum and minerals during the summer. Mr. Wantland is licensed by the State of Colorado as a geophysical engineer, and holds memberships in the Society of Exploration Geophysicists (regional editor 1942–); the American Association of Petroleum Geologists, and the Seismological Society of America.

W. HARLAN TAYLOR



DART WANTLAND

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the Society. This publication does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the Secretary within thirty days. (Names of sponsors are placed beneath the name of each nominee.)

ACTIVE

Volney Archibald Acheson
Norman Ricker, F. G. Boucher, E. M. McNatt

Lynn Dixon Allen
(Article III-D-1 of the Society Constitution)

Lewis Henry Boyd
Hart Brown, L. W. Saunders, H. R. Thornburgh

Andrew Brown
F. F. Reynolds, E. V. McCollum, Craig Ferris

Albert Joseph Zijdenstad Caan
W. W. Hardy, D. C. Skeels, Hart Brown

Festus Farnsworth Calhoun
A. C. Swearingen, J. Rudolph Johnson, John L. Bible

Lou Guynn Cornish
T. A. Manhart, A. J. Barthelmes, Stanley W. Wilcox

H. E. Hawkes, Jr.
Hans Lundberg, Louis B. Slichter, W. K. Hastings
Clyde Lloyd Hays
John L. Bible, A. C. Swearingen, J. Rudolph Johnson
Varnakale Lorenzo Jones
Stanley W. Wilcox, E. V. McCollum, Stefan VonCroy
James Alvin Long
Karl Dyk, C. E. Buffum, O. W. Anderson
John Charles Maher
Chalmer J. Roy (Article III-D-1 of the Society Constitution)
William A. Matthews
Karl Dyk, M. B. Widess, Joseph A. Sharpe
Glenn Merle McGuckin
William C. Woolley, Paul E. Nash, Wesley H. Seifert
Matthew Thomas Murray
C. A. Heiland, R. Maurice Tripp, W. S. Levings
Julian Kingsbury Pawley
J. W. Thomas, G. A. Berg, G. W. Carr
Harold Henry Pentz
Maurice Ewing, T. A. Manhart, Stefan VonCroy
Wendell John Pfeffer
R. H. Tallman (Article III-D-1 of the Society Constitution)
James Russell Reeves
Richard Williams, Edward L. DeLoach, B. G. Hubner, Jr.
Robert Russell Rosenkrans
F. F. Reynolds, H. H. Happel, John D. Marr
Edward George Schempf
Norman J. Christie, Raymond A. Peterson, C. Hewitt Dix
John Taylor Stanton-Ross
F. B. Leedy, T. A. Manhart, James E. Dorris
James Hopkins Todd
H. B. Peacock, Ewin D. Gaby, Virgil W. Teufel
Woodson Miller Tottenham
Paul E. Nash, William C. Woolley, Henry C. Cortes
Francis Rex Walling Jr.
Joseph A. Sharpe, Booth B. Strange, Neil R. Sparks

ASSOCIATE

Walter C. Bonebrake
E. D. Alcock, C. G. McBurney, R. D. Arnett
Grace Gertrude Mays
E. D. Alcock, C. G. McBurney, R. D. Arnett
Abdul Khaliq Mehta
C. A. Heiland, R. Maurice Tripp, W. S. Levings
Richard Edmound Francis Quinn
Harold H. Jones, R. S. Jackson, H. M. Falkenhagen
Albert Lee Wilkinson
W. O. Bazhaw, R. B. Pratt, Rudolph A. Weisbrich
James Neff Wilson
T. A. Manhart, A. J. Barthelmes, Stanley W. Wilcox

PERSONAL ITEMS

(Items for inclusion herein should be addressed to the Society at P.O. Box 1925, Washington, D. C.)

P. M. HONNELL, attached to the U. S. Army Signal Corps, has notified the Society of his advancement to the rank of Lieutenant Colonel on November 10. He is now stationed at the U. S. Military Academy at West Point as Property Officer and Officer-in-Charge of Laboratories in the Department of Chemistry and Electricity, and is primarily concerned with instructional facilities.

CHARLES E. DAY, Radio Engineer with the Crosley Corporation, is located in Cincinnati, Ohio. His mailing address is 6 Bachman Street, Cincinnati 18.

MICHAEL ALLON, of the Gulf Research and Development Co., has advised the Society of his expected removal from Pincher Creek, Alberta, Canada. Mail should be sent to P.O. Box 2038, Pittsburgh, Pennsylvania, for the present.

ROBERT BARLING has left the Miller Geophysical Co. to accept a position as Geological Scout with the Cities Service Oil Co. He is located in Tyler, Texas, at P. O. Box 779.

HENRY R. KIMBLE is with the Bureau of Ordnance, U. S. Navy Dept., Washington, D. C. He is residing at 2424 N. Florida St., Arlington, Virginia.

On November 15, Ensign H. J. MCCREADY advised the Society that he was stationed at Princeton N. J., where his address is Room 527, 03 Hall, Naval Training Station. He is retaining his permanent address as 4923 Knox Court, Denver, Colo.

EUGENE WIANCKO, Chief Computer on United Geophysical Co. Party 14 has been transferred from Odessa to Schulenberg, Texas, P. O. Box 446.

CHARLES G. LANGFORD is Draftsman and Computer for the Atlantic Refining Co., P. O. Box 2819 Dallas Texas.

G. R. BROTHERHOOD has left Trinidad Leaseholds Ltd., Pointe-a-Pierre, Trinidad, B. W. I., to return to England. There he will be located at 53 Baker St., Burton-On-Trent, Staffordshire.

LT. (JG) GEORGE C. MCGHEE, U. S. N. R., has moved from Dallas to 6305 Malvey, Ft. Worth, Texas.

ABDUL KHALIQ MEHTA, applicant for membership whose name appears in this issue, has left the Anchor Exploration Co. to accept a position as Computer and Observer with the National Geophysical Co., Tower Petroleum Bldg., Dallas, Texas.

P. M. KONKEL is with the Ohio Oil Co., Oil and Gas Bldg., Houston 2, Texas.

CAPT. HARRY R. IMLE, U. S. Army, is located at 1809 Dearborn St., Lawton, Okla.

M. L. BENKE has been advanced to the rank of Captain. His overseas address is Hq. 1st Island Air Command, APO 502, San Francisco, Calif. His home address remains 802 Waverly Ave., San Antonio 1, Texas.

E. J. HANDLEY has left the Continental Oil Co. to accept a position with the British-American Oil Producing Co., Philtower Bldg., Tulsa, Okla.

Advice has been received from S. K. VAN STEENBERGH, of the Sinclair-Prairie Oil Co., that mail for his organization and the Repollo Oil Co. should henceforth be addressed to 901 Fair Bldg., Ft. Worth 2, Texas.

WILLIAM E. WALLIS is being transferred from the West India Oil Co., San Jose, Costa Rica, to the Standard Oil Co. of Cuba, Apt. 1303, Havana, Cuba.

H. M. HOUGHTON is now Geophysical Supervisor with the Tide Water Associated Oil Co., P. O. Box 1404, Houston, Texas.

R. P. HEARIN, Seismograph Computer with the Phillips Petroleum Co., is located in Arkadelphia, Ark.

V. G. GABRIEL is now located at 447 S. Hope St., Los Angeles 13, Calif.

H. M. HOUSE, formerly with the Arkansas Fuel Oil Co., is now with Robert H. Ray, Inc. He is doing foreign work, and should be addressed in care of the Socony-Vacuum de Colombia, Aptdo. Aereo 4034, Bogota, Colombia, S. A.

A/C NEAL HARDIN, JR., who was with the Geotechnical Corp. when he made application to join the Society earlier this year, is on special training duty with the R. A. F. at Falcon Field, Mesa, Arizona. He expected to be commissioned in the latter part of November as a pilot in the U. S. Army Air Corps. He should be addressed at the Field in 15th A. A. F. F. T. O., Course 16-D.

PETER JACOBSEN, JR., of the Carter Oil Co., has been transferred from Douglas to Torrington, Wyoming.

LT. N. P. TEAGUE, on leave from the Stanolind Oil and Gas Co., is in the Hq. 11th Bomber Command, APO 980, Seattle, Wash.

GEORGE B. SOMERS has changed his mailing address from 1004 Rivermet, Ft. Wayne, Ind., to 4517 34th St. S Arlington, Va.

ROBERT W. JONES, of the Gulf Research and Development Co., is now located at B. O. Box 1965, Monahans, Texas.

W. BROOKE HAMILTON has left the Louisiana Land and Exploration Co. to enter business as an independent Lease Broker in Houston, Texas, where he is located at 636 Hawthorne Ave.

By V-Mail, JOHN V. LONG advises the Society that he has been advanced to the rank of Lieutenant Colonel. His address is Hq. 3rd Bn., 251st C. A. (A.A), APO 913, c/o Postmaster, San Francisco, Calif.

R. M. Low has left the Independent Exploration Co. to accept a position as Computer with the Seismograph Service Corp., in South America. His address is 21 Edificio Garcia Apts., Barranquilla, Colombia.

O. B. JACKSON, of the Shell Oil Co., is located at P. O. Box 518, Albany, Texas.

RICHARD L. DOAN has left Chicago, Illinois, and is now located at Oak Ridge, Tenn.

Newly elected officers of the Houston Geological Society, announced October 8, are: LESLIE BOWLING, Union Oil Co. of Calif., President; W. B. MILTON, JR., Gulf Oil Corp., Vice-President; W. B. MOORE, Atlantic Refg. Co., Secretary; and G. J. SMITH, Pan-American Prod. Co., Treasurer. Serving with the new officers is an Advisory Committee composed of S. G. GRAY, Tidewater Assoc. Oil Co., SHIRLEY L. MASON, Stanolind Oil and Gas Co., and JOSEPH HORNBERGER, JR., an independent.

ENS. WILLIAM I. MAYFIELD, U. S. N. R., has completed his training and is stationed at the U. S. Naval Armed Guard Center, New Orleans, La., awaiting assignment as commander of a Navy gun crew aboard an American merchant ship, Eighth Naval

District Headquarters announced recently. Prior to entering the service on April 26, he was serving as seismologist with the Petty Geophysical Engineering Co. of San Antonio. He is retaining his residence at 906 Camden St. in that Texas city.

KIRBY J. WARREN, JR. Geophysicist with the Carter Oil Co., has been transferred from Torrington to Douglas, Wyoming.

MAJOR LEONARD F. UHRIG should be addressed at C. A. T. S., Northwestern Univ., 357 E. Chicago Ave., Chicago 11, Ill.

JAMES J. ROARK, who has been serving as an Instructor in Electrical Engineering at the University of Arkansas, has returned to the Carter Oil Co., accepting a position as Jr. Research Geophysicist. His address is 723 S. Denver, Tulsa, Okla.

E. W. JOHNSON, of the Cities Service Oil Co., is located at P. O. Box 307, Kingman, Kansas.

V. G. FEATHER, Party Chief with the Phillips Petroleum Co., has left Colorado City, Texas, for Oklahoma City, Oklahoma, where he is located at 1232 First National Bank Bldg.

FRED FORWARD, another Phillips Party Chief, has been transferred from Conroe, Texas, to P. O. Box 547, Plaquemine, La.

LT. G. R. JOHNSON (S.B.), R.C.N.V.R., may be reached in care of C. F. M. O., 10 Haymarket, London, England. He is serving in the Canadian Naval Forces.

E. I. HEAD, Magnetometer Operator with the Gulf Research and Development Co., has been transferred from Three Rivers to Schulenberg, Texas, P. O. Box 23.

P. P. CONRAD, Gravity Party Chief with the Mott-Smith Corp., should be addressed in care of the Socony-Vacuum Oil Co., Aptdo. 246, Caracas, Venezuela, S. A.

PAUL CARTY REED, Seismic Party Manager with Gulf, has been transferred from Natchez to Box 167, Laurel, Miss.

W. M. WHITLEY, also with Gulf, has been transferred from Three Rivers to Schulenberg, Texas, P. O. Box 177.

WARREN H. SMITH, Computer with the Texas Co., has moved from Madera to Brawley, Calif., P. O. Box 202.

KENNEDY R. MARBLE is on foreign duty with the Tropical Oil Co., El Centro, Cartagena, Colombia, S. A.

At the September 30 meeting of the Houston Geological Society, J. ELMER THOMAS presented motion pictures of the Italian oil fields, as well as several reels showing the geology and geography of that part of Italy where fighting was currently in progress. JOSEPH HORNBERGER, JR., discussed "The Geology of the Oil Fields of Central Jackson County, Texas," also.

W. B. HEROY, who has been serving as Director of the Reserves Division of the Petroleum Administration for War, has been chosen to head the newly created Foreign Production Division of that organization. BASIL B. ZAVOICO, Assistant Director of Reserves, was earlier transferred to the Program Division. Both have their offices in the Interior Bldg., Washington, D. C.

THE CHAIRMAN OF THE NATIONAL RESEARCH COUNCIL, on recommendation of the Executive Committee of the Division of Geology and Geography, has approved the establishment in the Division of a Committee on Geological Personnel, effective July 30,

1943. The following is the present membership of the Committee: Henry R. Aldrich, Charles H. Behre, Jr., Kenneth C. Heald, A. I. Levorsen, William B. Heroy Chairman, W. W. Rubey, Chairman of the Division of Geology and Geography, *ex officio*.

The National Research Council was established by Executive Order of President Wilson May 11, 1918. Among the duties assigned to it were "to develop effective means of utilizing the scientific and technical resources of the country for dealing with (research) projects." The Nation has no greater resources of this character than its scientific and technical personnel and this quotation expresses the general purpose for which the Committee has been organized.

Following the general policies of the Council the Committee will function primarily for purposes of survey, planning and coordination. It will endeavor to develop close contacts with the activities in personnel matters of the various societies, institutes, foundations and other agencies in the field of geology. It will not seek to duplicate or to supersede their work and will undertake specific projects only if it may appear, after due consideration, that a cooperative arrangement under the Council is advantageous.

There is in the National Research Council an Office of Scientific Personnel, of which Dr. Homer L. Dodge is Director. This Office functions for the Council as a whole and Dr. Dodge has been engaged in a large range of activities concerned with the procurement of scientific personnel for various war agencies, the placement of scientific workers, and the administration of the War Manpower Commission. The Division of Geology and Geography, through the assistance of the Geological Society of America, will share in the activities of the Office of Scientific Personnel and will obtain the valued assistance of Dr. Dodge in specific personnel problems.

STATEMENT OF THE OWNERSHIP, MANAGEMENT, CIRCULATION, ETC., REQUIRED BY THE ACTS OF CONGRESS OF AUGUST 24, 1912, AND MARCH 3, 1933

of GEOPHYSICS, published quarterly at Menasha, Wisconsin, for January, 1944

City of Washington } ss.
District of Columbia }

Before me, a Notary Public in and for the State and county aforesaid, personally appeared J. F. Gallie, who, having been duly sworn according to law, deposes and says that he is the business manager of GEOPHYSICS and that the following is, to the best of his knowledge and belief, a true statement of the ownership, management (and if a daily paper, the circulation), etc., of the aforesaid publication for the date shown in the above caption, required by the Act of August 24, 1912, as amended by the Act of March 3, 1933, embodied in section 537, Postal Laws and Regulations, printed on the reverse of this form, to wit:

1. That the names and addresses of the publisher, editor, managing editor, and business managers are: Publisher, George Banta Publishing Company, Menasha, Wisconsin; Editor, Joseph A. Sharpe, P. O. Box 591, Tulsa, Oklahoma; Managing Editor Joseph A. Sharpe, P. O. Box 591, Tulsa, Oklahoma; Business Manager, J. F. Gallie, P. O. Box 1925, Washington, D. C.

2. That the owner is: Society of Exploration Geophysicists, P. O. Box 1925, Washington, D. C.; R. D. Wyckoff, Box 2038, Pittsburgh, Pa. (President); W. M. Rust, Jr., Box 2180, Houston, Texas (Vice-President); F. Goldstone, Box 2099, Houston, Texas (Past President); Joseph A. Sharpe, Box 591, Tulsa, Okla. (Editor); Hart Brown, Box 6055, Houston, Texas (Secretary-Treasurer).

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4. That the two paragraphs next above, giving the names of the owners, stockholders, and security holders, if any, contain not only the list of stockholders and security holders as they appear upon the books of the company but also, in cases where the stockholder or security holder appears upon the books of the company as trustee or in any other fiduciary relation, the name of the person or corporation for whom such trustee is acting, is given; also that the said two paragraphs contain statements embracing affiant's full knowledge and belief as to the circumstances and conditions under which stockholders and security holders who do not appear upon the books of the company as trustees, hold stock and securities in a capacity other than that of a bona fide owner; and this affiant has no reason to believe that any other person, association, or corporation has any interest direct or indirect in the said stock, bonds, or other securities than as so stated by him.

5. That the average number of copies of each issue of this publication sold or distributed, through the mails or otherwise, to paid subscribers during the twelve months preceding the date shown above is not required. (This information is required from daily publications only.)

J. F. GALLIE (Signed)

Sworn to and subscribed before me this 2nd day of October 1943.

[SEAL] LAUREALMO P. POSTER (Signed

(My commission expires Jan. 15, 1944.)